# RESEARCH AND DEVELOPMENT IN FLUID LOGIC ELEMENTS

Technical Summary Report

November 16, 1964

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George C. Marshall Space Flight Center Huntsville, Alabama

(Prepared under Contract No. NAS8-11021 by the Special Devices Department, UNIVAC Division of the Sperry Rand Corporation, Blue Bell, Pa., T. Reader, Author)

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### ABSTRACT

The evolution of machines is traced from earliest times to the present. It has been shown that some machines have become less dependent on the mechanical properties of their interacting parts and more on the subtle use of techniques which eliminate the possibility of breakdown through wear. Electronics achieved this by eliminating all macroscopic motion, while fluids achieved a similar result by eliminating all sliding and impingement of solid surfaces.

Multistate fluid logic elements help to fill the gap between digital techniques and direct mechanical control. Analysis has shown that the performance of low-gain and multioutput elements may be predicted and that these elements provide the advantages of reasonable speed and fan-out with an insensitivity to small variations in element geometry not shown by the highergain fluid elements.

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# CONTENTS

Heading	Title	Page
	SECTION 1. MACHINES AND SYSTEMS	
1-1.	Historical Background	1-1
1-2.	A Brief History of Fluid Amplifiers	1-5
1-3.	The Study of Multistate Fluid Logic Ele-	
	ments	1-6
\$	SECTION 2. DEVELOPMENT OF MULTISTATE ELEMENTS	
2-1.	Statement of Program	2-1
2-2.	Experiments with Three-Dimensional Ele-	
	ments	2-1
2-3.	Experiments with the Polygonal Element	2-3
2-4.	Experiments with the Aerosonic Device	2-4
	SECTION 3. THE EVOLUTION OF AN ANALYTICAL APPROACH TO FLUID SYSTEMS	
3-1.	General	3-1
3-2.	Reynolds Number	3-2
3-3	Flow Gain	3-2
3-4.	Pressure Gain	3-3
3-5.	Aspect Ratio	3-3
3-6.	Fan-Out	3-3
3-7.	Number of Stable States	3-4
3-8.	Power	3-4
3-9.	Sensitivity to Variations in Geometry	3-4
3-10.	Suitability for Integrated Circuitry	3-5
3-11.	Switching Speeds	3-5
3-12.	Proposed Empirical Relationships	3-6

Heading	Title	Page
3-13.	Determination of Minimum Power Required	0.7
2 14	Per Element	3-7
3-14.	Designing a Fluid System	3-7
3~15.	The Effect of Sonic Propagation Velocity	3-12
	SECTION 4. LOGIC AND ALGEBRA STUDIES	
4-1.	Description of Three Multistate Elements	4-1
4-2.	Some Applications of Multistate Ele- ments	4-4
4-3.	Asynchronous Logic	4-16
4-4.	The Biquinary System	4-16
	SECTION 5. A THEORETICAL FOUNDATION FOR FLUID LOGIC ELEMENTS	
5-1.	Trends in Fluid Digital Logic	5-1
5-2.	Trends in Fluid Element Design	5-4
	SECTION 6. THE DESIGN PHILOSOPHY OF FLUID AMPLIFIERS	
6-1.	The Wall Effect	6-1
6-2.	The Turbulence Amplification Principle	6-3
6-3.	Control Jet Reaction	6-4
6-4.	The Need for a Workable Theory	6-5
6-5.	The Momentum Exchange Principle	6-6
6-6.	The Control Jet Reaction Principle	6-9
6-7.	The Nozzle Reaction Principle	6-11
6-8.	Transient Response	6-15
	SECTION 7. DEVELOPMENT OF A FLUID ELEMENT	
7-1.	Optimization of Fluid Elements	7-1
	SECTION 8. EXPERIMENTAL RESULTS	
8-1.	Steady State Characteristics	8-1
8-2.	Transient Response	8-4

Heading	Title	Page
	SECTION 9. CONCLUSIONS AND RECOMMENDATIONS	
	APPENDIX A. THE NASA FLUID ARITHMETIC UNIT	
A-1.	General Description	A-1
A-2.	S Register	A-1
A-3.	The Accumulator	A-1
A-4.	Binary Adder	A-5
A-5.	Control	A-5
A	PPENDIX B. DEVELOPMENT OF DUAL-OUTPUT INVERTER	
B-1.	General	B-1
B-2	Conclusion	B-4
	APPENDIX C. DUAL-OUTPUT INVERTER	
C-1.	Introduction	C-1
C-2.	Design Concept	C-1
C-3.	Performance Characteristics of DOI No. 2	C-4
C-4.	Dynamic Performance	C-5
C-5.	Suggestions for Further Development	C-16
	APPENDIX D. EVALUATION OF DYCRIL PROCESS FOR MAKING TEMPLATE	
D-1.	Introduction	<b>D-</b> 1
D-2.	Dimensional Tolerance of DYCRIL Process	D-1
D-3.	Conclusions	<b>D</b> -10
	•	

APPENDIX E. REFERENCES

# LIST OF ILLUSTRATIONS

Figure	Title	Page
1-1.	Design-Life Chart	1-3
2-1.	Three-Dimensional Four-Output Memory Element	2-2
2-2.	Polygonal Four-Output Memory Element	2-3
2-3.	Aerosonic Device	2-4
2-4.	Apparatus for Testing Large-Scale Models	2-7
2-5.	Three-State Model (Jet in Central Position)	2-8
2-6.	Three-State Model (Jet Attached to Left-Hand Wall)	2-9
2-7.	Three-State Model (Jet Attached to Right-Hand Wall)	2-10
2-8.	Three-State Model (Improved Design)	2-11
2-9.	Magnified View of Adjustable Element	2-12
4-1.	Three-State Memory Element ,	4-1
4-2.	Two-Input, Three-Output (2-3) Passive Element	4-2
4-3.	Passive AND Gates Equivalent to a 2-3 Element	4-2
4-4.	Three-Input, Five-Output 3-5 Passive Element	4-3
4-5.	Passive AND Gates Equivalent to a 3-5 Element	4-3
4-6.	Two Cells of a Queueing Register	4-5
4-7.	Single Stage of a Queueing Register	4-5
4-8.	Two Cells of a Queueing Register Using Fluid Elements	4-7
4-9.	Section of an Actual Queueing Register Circuit	4-8
4-10.	Full Adder Circuit Using Conventional	4.0

Figure	Title	Page
4-11.	Diagram of a Full Adder Circuit With 2-3 Gates	4-10
4-12.	Full Adder With 2-3 Gates	4-11
4-13.	Diagram of a Full Adder With 3-5 Gates	4-12
4-14.	Full Adder With 3-5 Gates	4-13
4-15.	Full Adder Using NOR Gates Only	4-14
4-16.	Full Adder Using Dual-Output Amplifier and 2-3 Elements	4-14
4-17.	Two Different Flip-Flops	4-15
5-1.	Four Low-Gain Elements	5-2
5-2.	Fan-In and Fan-Out Circuits	<b>5-</b> 3
<b>5</b> -3.	Three Multistate, Non-Memory Logic Elements	<b>5-</b> 3
6-1.	Two Methods of Deflecting a Power Set	6-2
6-2.	Deflections Produced by a Control Jet	6-2
6-3.	Breakdown of a Laminar Power Jet by means of a Control Jet	6-3
6-4.	Deflecting a Power Jet by means of a Control Jet	6-4
6-5.	Interaction of two Free Jets	6-6
6-6.	Deflection of a Power Jet Curtain	6-9
6-7.	Effect of Power Nozzle Wall Reaction	6-12
7-1.	Stages in the Construction of a Plastic Element	7-3
7-2	3-5 Element	7-4
7-3.	Tristable Memory Element	7-5
7-4.	Dual-Output Amplifier	7-5
7-5.	Three-Output 2-3 Element	7-6
7-6.	Low Gain 2-2 Element	7-7
8-1.	Steady State Characteristics of a Three- Output Memory Element	8-1
8-2.	Steady State Characteristics of a 2-3 Element	8-2
8-3.	Steady State Characteristics of a	8-3

Figure	Title	Page
8-4.	Steady State Characteristics of a Dual- Output (High-Gain) Amplifier	8-3
8-5.	Study State Characteristics of a 2-2 (Low-Gain)Element	8-4
8-6.	Transient State Characteristics Giving Cycle time of a Low-Gain Oscillator	8-5
A-1.	Four-Bit Binary Adder	A-3/A-4
A-2.	Relative Timing	A-5
A-3.	Fluid Arithmetic Unit	A-6
B-1.	Template for DOI No. 1 Design	B-2
B-2.	Test Arrangement (Without Isolator)	B-3
B-3.	Test Arrangement (With Isolator)	B-3
B-4.	Performance Characteristics of DOI  No. 1 Design	B <b>-4</b>
C-1.	Test Arrangement	C-4
C-2.	DOI No. 2 Design	C-5
C-3.	Device No. O Static Characteristics (Output Blocked)	C-6
C-4.	Device No. O Static Characteristics (Output Blocked)	<b>C-</b> 7
C-5	Device No. O Static Characteristics (Loaded with 0.030 Orifice)	C-7
C-6.	Device No. O Switching Test (Output Blocked)	C-8
C-7.	Variations in Power Gain	C-8
C-8.	Impedance of the Control Channel Versus Frequency of Operation	C-9
C-9.	Device No. 1 Static Characteristics (Output Blocked)	C-9
C-10.	Device No. 2 Static Characteristics (Output Blocked)	C-10
C-11.	Device No. 1 Static Characteristics (Output Blocked)	C-11
C-12.	Device No. 2 Static Characteristics (Output Blocked)	C-12
C-13.	Device No. 1 Switching Test (Output Blocked)	C-12

Figure	Title	Page
C-14.	Device No. 2 Switching Test (Output Blocked)	C-13
C-15.	Device No. 1 Static Characteristics (Loaded with 0.030 Orifices)	C-13
C-16.	Device No. 2 Static Characteristics (Loaded with 0.030 Orifices)	C-14
C-17.	Flow Recovery	C-14
C-18.	Variations in Power Gain	C-15
D-1.	Template for DOI No. 2 Design	D-2
D-2.	Schematic Showing Exposure of the DYCRIL Plots	D-3
D-3.	Top View of the Test Block	D-4
D-4	Block No. 1, End View	D-5
D-5.	Block No. 2, End View	D-6
D-6.	Block No. 3, End View	D-7
D-7.	Block No. 4, End View	D-8
D-8.	Cross Section of the Test	D-10
	TABLES	
Table	Title	Page
C-1.	Test Data-Design H, 0.400 Inch Model. As-	C-3

#### SECTION 1

#### MACHINES AND SYSTEMS

### 1-1. HISTORICAL BACKGROUND

Man probably first realized he could exert control over his environment when he found that it was possible to employ a lever to move a seemingly immovable object. Since that time man has learned to control vastly more complicated machines.

Not long after man's conquest of some of his physical limitations he began to see the advantages of using stones to count, and soon the abacus was invented. While the machines became more and more sophisticated it seemed that man was unable to improve on the abacus for several thousand years. The main limitation was the physical difficulty of designing machines which could handle beads automatically.

Eventually, by means of gears and levers, it was found possible to count and then to add by means of machines. The trend toward ever-increasing complexity became most marked in the nineteenth century, when the general feeling was that everything that was possible to do could be done with a mechanical device or at least could be explained in terms of Newtonian mechanics.

A climax in mechanical complexity came during the 1820's when Charles Babbage attempted to build a "difference engine," which was in essence a mechanical computing machine. He might well have succeeded had the technology of the day been advanced enough to meet demanding requirements of his machine. More complex mechanical machines have since been invented but none typified the futility of mechanical complexity as thoroughly as did the Babbage difference engine.

The turn of this century marked the downfall of deterministic mechanics and the rise of such new ideas as relativity, uncertainty, and probability.

These ideas affected man psychologically as well as environmentally. Man now looked at the world not as a complex, determinate mechanism capable of finite, if lengthy, analysis and ultimate solution but as a system in which redundancy and the evolutionary process resulting from the coincidence of highly improbable events were the very substance of reality.

With his new-found freedom the thinking man was now willing to commit scientific "heracies" for he knew that Aristotle was grounded for good and that the church would certainly not interfere with any new scientific theories unless they appeared to threaten man's concept of the devine will. Unfortunately the theories were becoming so complex that the layman could no longer follow them still less know whether they posed as a threat to his religious convictions; consequently, he began to feel that science should be left to the specialist.

The fruits of scientific liberation from the fetters of Newtonian determinism were slow to ripen. Many scientific fields were bound by a rigid structure of dogma and authority. Mathematics and nuclear physics were the first to gain freedom, and together have revealed to man such phenomena as atomic energy and nuclear radiation. It is to be hoped that the other sciences, such as government and economics, will achieve comparable gains before a neglected coincidence of events results in a termination of all progress. Once again man finds himself deeply involved in the mutually implicative problems of science and society.

Throughout the scientific upheavals of the last two centuries the mechanism has made relentless progress. Its only limitation has been slowness and a tendency to wear out. Figure 1-1 shows a Design-Life Chart in which it can be seen that for machines that contain sliding and reciprocating parts operating speed can be obtained only at the expense of accumulated cycles. Also illustrated in the chart is the fact that machines in which the relative velocity of different materials is kept low can operate at high speed and still achieve a large number of accumulated cycles.

The loud-speaker has an almost unlimited life because it contains no sliding parts. It is conceivable that rotors supported on fluid bearings to prevent direct sliding contact would have comparable design life. Electronic devices contain no moving parts and therefore their life is limited not by wear but by physical deterioration of the materials used. The same is true of pure fluid devices, which are the subject of this discussion.

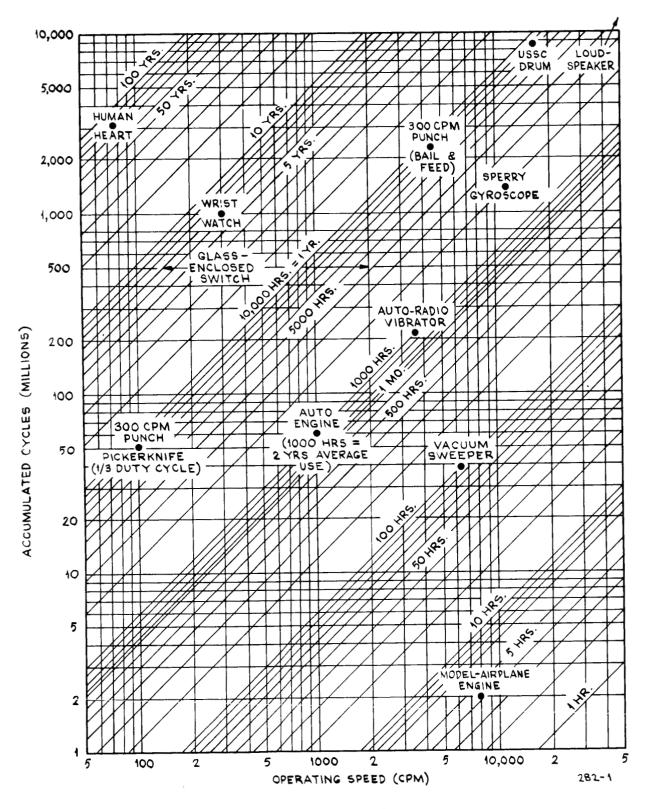


Figure 1-1. Design-Life Chart

Control of man's environment can be achieved not only by the direct manipulation of levers and buttons but by "programmed sequences" built into the machine which save man the effort of carrying out many automatic cycles of action. These programmed sequences can be either analog, digital, or a combination of both. For example, some automatic transmissions used in cars employ an analog torque converter together with a two-speed automatic gear shift.

It is clear that automatic sequences depend on digital operation while adaptive processes, such as error correction or position sensing, rely on analog operation. With the advent of ultra high speed digital computers, it has been found that many functions formerly performed on analog devices can now be performed digitally. The advantage of digital devices is that the errors associated with analog devices can be completely avoided. Problems of guidance in which a complete trajectory must be predicted at frequent stages in the flight of a space vehicle can be solved digitally more easily than by analog means and with far greater accuracy.

The use of fluids in performing computation functions offers many advantages over that of electronic devices. Fluid devices are ultrareliable, insensitive to electromagnetic fields, use little power, and are capable of direct coupling to appropriate sensors and effectors. The speed of fluid digital devices, although much slower than their electronic counterparts, is still fast enough for sequencing functions. Any system employing fluids is likely to depend more heavily on analog operation than would a system employing electronics. The reasons for this are twofold: First, d-c electronic analog devices are susceptible to drift, and a-c electronic devices are not very adaptable to analog computation. This is not true of fluid devices, which lend themselves ideally to analog operation. Second, electronic devices are so fast that it is possible to operate them at cutoff and at saturation only and thereby eliminate the problem of drift by resorting to digital operation. Fluid devices exhibit characteristics entirely different from those of electronic devices: Fluid devices do not drift, their characteristics do not change with age or environment, but they are slower. It is natural then that the analog-digital mix for a fluid system would be different from the analog-digital mix for an electronic system.

A factor which would certainly affect the choice of devices to be used in a system would be the need for ultrareliability and adequate speed.

Fluid devices show indications of being more reliable than any other devices yet invented. It is for this reason that both analog and digital fluid devices must be developed and ultrareliable systems demonstrated, if costly system failure is to be an extremely rare event rather than an almost expected event.

## 1-2. A BRIEF HISTORY OF FLUID AMPLIFIERS

The major breakthrough in fluid amplifier research was made by the Diamond Ordnance Fuze Laboratories in 1960 with the development of a fluid amplifier which uses no moving parts. Immediately, it appeared that the new fluid amplifier would fill the gap which existed between the slow mechanical devices used in control equipment and calculating machines and the unnecessarily fast and expensive electronic devices used in high-speed computers.

Initially, much progress was made in fluid amplifier research: Many inventions were announced, and hundreds of papers were written. It was found that fluid amplifiers could be modified to give an almost unlimited variety of d-c characteristics. Problems which involved the interconnections of complex circuits were encountered and systematically solved.

About two years later Raymond N. Auger<sup>1</sup> completed development of his turbulence amplifier; this amplifier reaffirmed the importance of input and output isolation. It now appeared that all circuit problems had been solved and that the only remaining problems were speed improvement and fabrication. However, the turbulence amplifier had two major disadvantages: It could not be fabricated as cheaply as would have been desired, and it was slow to recover its full output signal strength once the control signal had been removed.

When the initial results of early fluid amplifier investigations were announced, evaluations made by UNIVAC engineers disclosed the serious high-speed limitations of pure fluid digital devices. It later appeared that fluid devices were not even as fast as mechanical devices. UNIVAC had been investigating the feasibility of using fluid devices to control magnetic tape by switching air between two counter-rotating capstans. Electromechanical valves had already been developed which could switch in less than half a millisecond. It was felt that by eliminating moving parts altogether even higher speeds could be obtained. Early tests carried out by UNIVAC showed

that the switching time of the pure fluid flip-flop was approximately one millisecond.

A comprehensive program was then established to develop a high-speed pure fluid logic device. An entirely new approach, which employed the "edgetone" effect, was conceived, and a device was built whose aim was to achieve speeds comparable to the half-period of the edgetone frequency. This device showed that speeds could be improved and that an understanding of the basic edgetone phenomenon could lead to a useful high-speed element. Because the edgetone phenomenon is extremely complicated, several mathematical and theoretical studies are presently underway to clarify the directions for future development.

A parallel effort in the quest for higher speeds in fluid devices resulted in the UNIVAC inverter. This device achieved a switching speed of about a third of a millisecond; its chief characteristics were the increased effectiveness of the control signal, and, consequently, a reduced dependence on wall lock-on effects. Although this speed increase was not dramatic, it did point the way to a promising means of improving fluid amplifier performance. A further step toward the development of a useful high-speed device was the fabrication of a NOR gate, which was built by combining a four-input OR gate with a UNIVAC inverter. The design of the OR gate was such that complete isolation of all four inputs was achieved. The gain of the inverter was sufficient to permit each NOR gate to drive four other NOR gates, and the inverter was found to be sufficiently insensitive to output load that no problems were encountered in assembling complex circuits.

Unfortunately, the addition of the four-input OR gate to the inverter increased the switching time of the resulting NOR gate to almost one millisecond, and it appeared that little progress had been made in terms of speed. However, progress in such areas as fabrication, experimental and analytical techniques, and design methods was being made, but speed remained a major difficulty.

## 1-3. THE STUDY OF MULTISTATE FLUID LOGIC ELEMENTS

Some time ago NASA suggested that perhaps our approach should be centered less on the use of binary devices, which owed their success in electronic computers to an essentially two-state mode of operation, and more on multistate

devices, which are based on the completely different principles involved in the operation of interacting jets enclosed by walls.

Multistate elements proved more difficult to design than had been anticipated. Most of the early attempts resulted in devices whose steady-state characteristics failed to meet even the barest design specifications. It soon became clear that the difficulties which had been encountered in designing a satisfactory flip-flop were compounded in the design of a tristable element.

Logical design studies in multistate elements showed that although a tristable element had an advantage over more conventional elements as far as design of an asynchronous shift register was concerned, its use in general was limited. A more useful device would be a trilevel element which could enhance the use of the more logically powerful ternary arithmetic and its associated algebra. Depending on its control signals, the UNIVAC aerosonic device was capable of producing three different output levels, and it was felt that this device might form the basis of a useful three-level element. Tests of this element showed that while three-level operation was extremely sensitive to small geometry variations, three-state operation could easily be obtained by simply replacing the central splitter responsible for the edgetone by a receiver to form a third output. UNIVAC now had a three-state element with limited logical utility.

Several three-state elements were built, and an asynchronous shift register was assembled by use of these elements and NOR gates. Dynamic tests showed, however, that the three-state element was even slower than the conventional flip-flop, and the search for a new principle of operation continued.

The switching speeds of active elements appeared to be of the order of one millisecond for a power nozzle width of 0.020 inch; however, tests on passive elements employing momentum exchange showed that speeds could be reduced to one tenth of a millisecond, if the wall attachment effects were eliminated. This discovery led to the development of two multistate logic elements whose operation depended only on the exchange of momentum between the input jets. It soon became evident that the speed of a fluid logic circuit depended almost as much on the amount of logic which could be accomplished at each jet interaction region as on the speed of the individual elements.

We are at the crossroads in fluid amplifier development; on the one hand we have elements with very high gain and poor switching speed, and on the other hand we have elements with very high switching speed and poor gain. The former elements have been conventionally classed as active, while the latter elements have been classed as passive; however, in the light of recent discoveries, this distinction has become less meaningful. What is now anticipated is a synthesis of active and passive principles so that high speed is combined with adequate gain.

#### SECTION 2

#### DEVELOPMENT OF MULTISTATE ELEMENTS

## 2-1. STATEMENT OF PROBLEM

As soon as the project was begun the problem was divided into two phases: the development of elements having three or more stable states and the investigation of the logical design problems which would result. Phase 1 of the contract consisted of studies and experimental work to establish the logic rules and feasibility of construction of logic elements with three or more stable states. The maximum number of stable states which is practical by use of fluid logic devices was determined.

Phase 2 consisted of defining the mathematical concepts required for a logic system utilizing the selected number of stable states. Experimental work was accomplished showing the feasibility of utilizing this higher order logic to accomplish addition, subtraction, counting, shifting, and so on.

We shall review, historically and critically, the research in multistate elements; we shall also criticize, in the light of subsequent findings, the manner in which the work was carried out. In this way relevant data obtained later in the program will be introduced to clarify areas where the nature of the problem was not fully appreciated at the time.

#### 2-2. EXPERIMENTS WITH THREE-DIMENSIONAL ELEMENTS

Early experiments with the DOFL-type flip-flop demonstrated that even two-state operation of fluid devices was extremely critical and that without a means of isolating the outputs the circuit problems resulting from loading sensitivity were such that the building of complex working systems was an extremely arduous task.

Because we had found great difficulty in designing a satisfactory two-dimensional flip-flop or two-state element, we decided that there would be little point in designing a two-dimensional three-state element. A three-dimensional device was therefore designed and tested. It was our hope that with the increased freedom of a third dimension many of our problems would disappear.

Figure 2-1 shows a diagrammatic representation of the design tested. It appeared that stable operation of the device was difficult to achieve because of the poor attraction which can be exerted by the inside wall of a

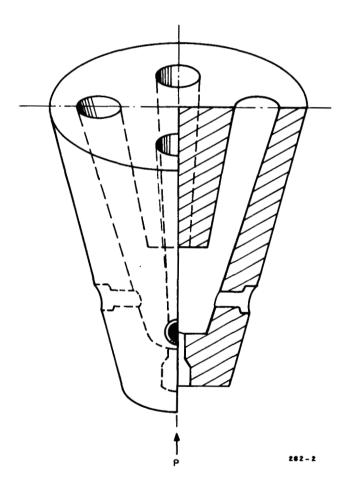


Figure 2-1. Three-Dimensional Four-Output Memory Element

hollow cone on a circular jet. Attempts were made to increase the multistability of the jet by providing regions of low pressure in the interaction zone, but no success was achieved. It was concluded at that time that three-dimensional multistable devices would require further engineering design; as a consequence, attention was then focused on two-dimensional elements.

## 2-3. EXPERIMENTS WITH THE POLYGONAL ELEMENT

Figure 2-2 shows an early concept of the polygonal element as envisioned in the proposal. It was found that the pressure recovered at the last output fell rapidly as the number of polygonal sides increased. The relationship

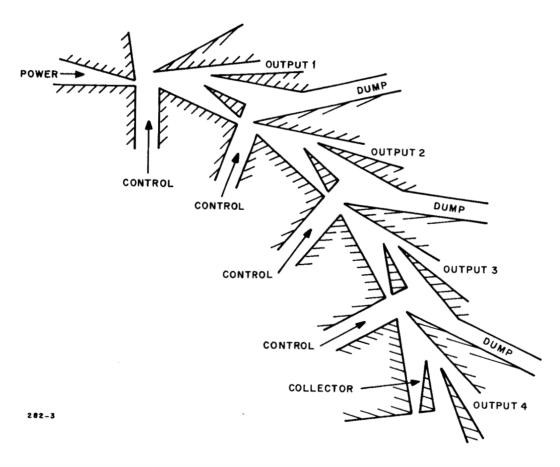


Figure 2-2. Polygonal Four-Output Memory Element

giving the final output pressure  $\boldsymbol{p}_0$  as a function of the supply pressure  $\boldsymbol{p}_S$  and the number of polygonal sides n was found to be

$$p_0 = p_s(0.45)^n$$

Thus, with four polygonal sides and a supply pressure of 20 inches of water

$$p_0 = 20(0.45)^4$$
= 0.825 inch

It appeared that the polygonal element had little to offer, since all the outputs were at different levels. Its capacity to drive other similar elements depended not only on the output level available but also on the point within the polygon where the input signal was applied.

Work done later showed that in some instances it is economical to cascade passive elements and thereby form a special-purpose multistate element. The polygonal element is one example of a series of inverter-type elements in which the output of one element supplies the power for a second element the output of which supplies the power for a third element and so on. This form of cascading is necessarily less effective than the form in which the power for each passive element is supplied from the output of an active element where there is no decay of signal strength throughout the cascade and, consequently, no limit to the extent of cascading permissible.

### 2-4. EXPERIMENTS WITH THE AEROSONIC DEVICE

This device was originally conceived as an ultra high-speed fluid logic element. Figure 2-3 shows the basic geometry. If the power jet is turned on in the absence of control signals at either D or E, the flow will oscillate

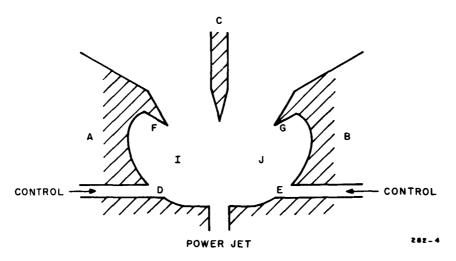


Figure 2-3. Aerosonic Device

about the central wedge at a frequency determined by the supply pressure and the wall geometry. Experiments have shown that this frequency is several orders of magnitude faster than would be obtained from a multivibrating flip-flop of conventional design.

The principle involved in these experiments is that three stable states are possible. With both control jets D and E open the power jet oscillates about the central wedge. When control port D is closed the power jet is drawn to the left by the differential pressure on either side of the power jet; this differential pressure results from a difference of entrainment within the cavities I and J. When control port D is open and control port E is closed the jet is drawn to the right.

By varying the geometry of the element it is possible to achieve three stable states:

- 1. Flow from left side only
- 2. Flow from right side only
- 3. Flow divided equally between left and right sides

This phenomenon had long been observed by UNIVAC engineers, and it was felt that it might form the basis of a multilevel element in which each of the two outputs could have three levels corresponding to zero flow, half flow, and full flow, respectively.

It appreared that wedge C was the critical component in the element, since very slight asymmetry of this wedge resulted in a complete change of device characteristics. The design approach at this point required the complete removal, where possible, of any component which caused trouble. By removing the central wedge it was still possible to obtain three-level operation by the expedient of splitting the flow after collection rather than in the critical region of the device itself.

Without the central wedge the performance of the device was much more reliable. However, it was still difficult to obtain the desired characteristics. In order to obtain the central output it was necessary either to apply control pressure at both inputs and then to remove the control pressure from both sides simultaneously or to turn off the power supply and then to turn it on in the absence of control signals.

The apparatus used for testing this design is shown in Figure 2-4. Air was applied to the power supply of the model by means of two Lamb electric blowers contained in the wooden casing shown. A mist generator, which is shown to the right of the test apparatus, is used for generating a kerosene mist by heating liquid kerosene to boiling point and collecting the vapor in a bottle. The vapor was then passed into the main power stream where it condensed into a mist and made flow visualization possible.

Figure 2-5 shows the power jet unattached to either wall. This state was attained by turning on the power jet in the absence of any control signals. Figure 2-6 shows the power jet attached to the left-hand wall of the device. This state was attained by applying control pressure to the right-hand vortex chamber, and Figure 2-7 shows the power jet attached to the right-hand wall.

Figure 2-8 shows an improved design of a three-output element containing a five-inch-by-five-inch nozzle. Flow visualization for the design of this device was achieved in the same manner as for the design of the element shown in Figures 2-5, 2-6, and 2-7.

It was possible to set the element to any one of its three stable states by means of pulses applied at the control inputs,  $B_i$  and  $C_i$ . If the element was in its  $B_0$  state, a short pulse applied at  $C_i$  would reset the element to its  $R_0$  state. However, to change the state of the element from  $B_0$  to  $C_0$ , it was necessary to apply a long pulse at  $C_i$ . Similarly, to change the state of the element from  $C_0$  to  $B_0$ , it was necessary to apply a long pulse at  $B_i$ . The element could also be reset to its  $R_0$  state by applying either short or long pulses at both  $B_i$  and  $C_i$ . In this case it was important that the input signals be removed simultaneously.

A three-state fluid device with a 0.030-inch-by-0.120-inch nozzle was developed (see Figure 2-9). Tests showed that this device would operate successfully in an asynchronous logic circuit called a queueing register, which will be described in Section 4.

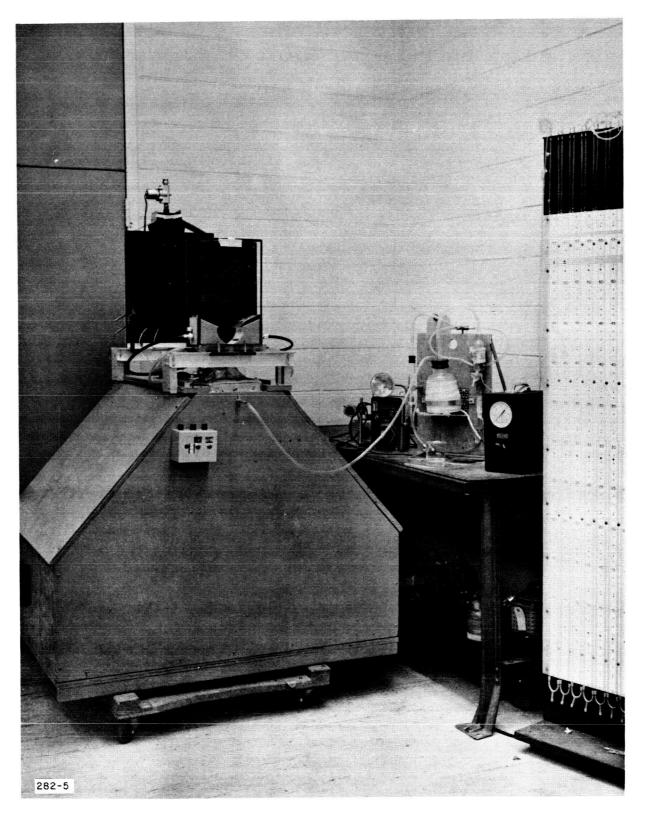


Figure 2-4. Apparatus for Testing Large-Scale Models

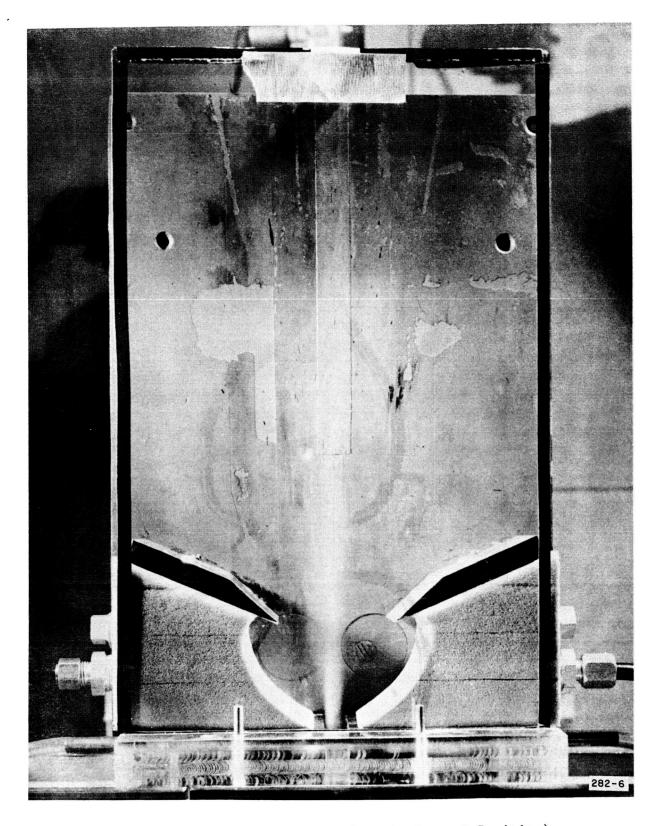


Figure 2-5. Three-State Model (Jet in Central Position)

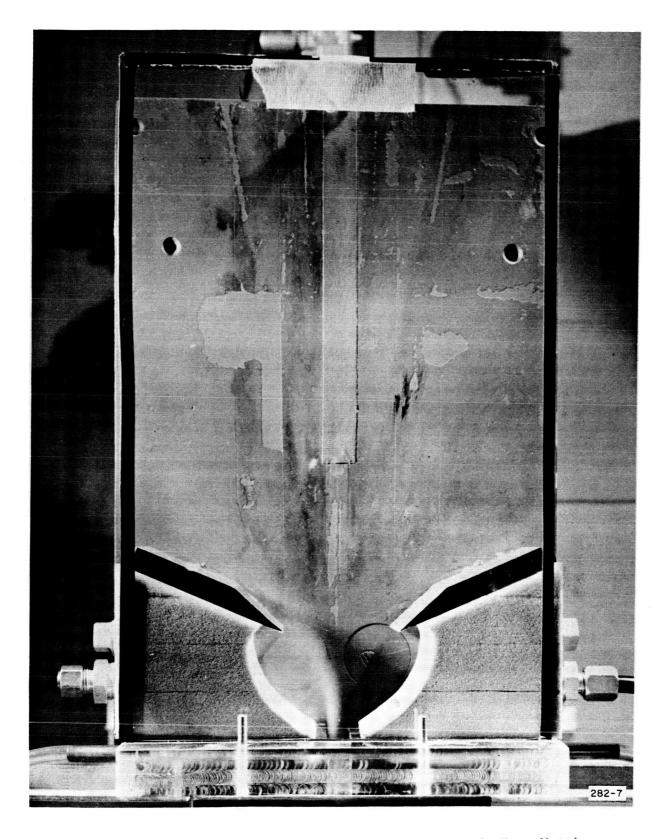


Figure 2-6. Three-State Model (Jet Attached to Left-Hand Wall)

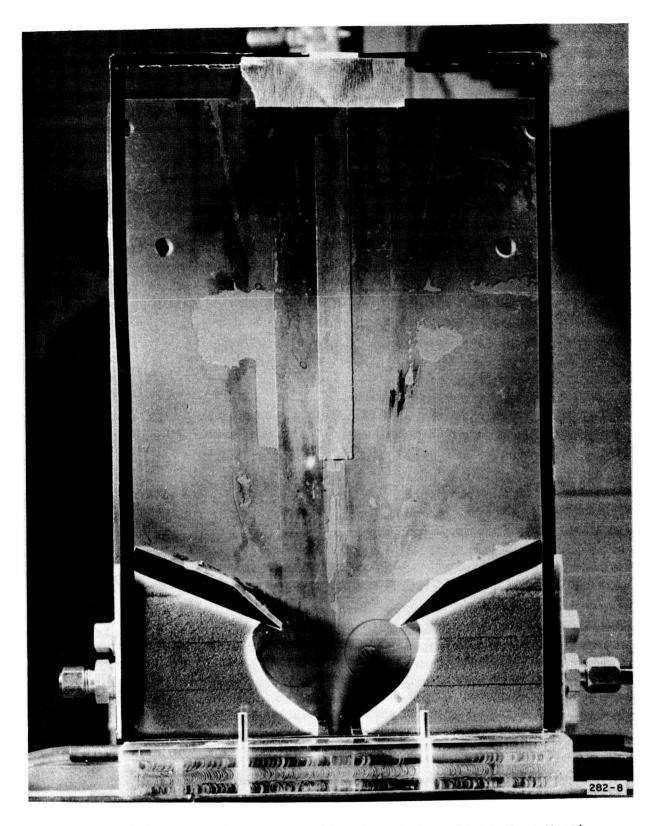


Figure 2-7. Three-State Model (Jet Attached to Right-Hand Wall)

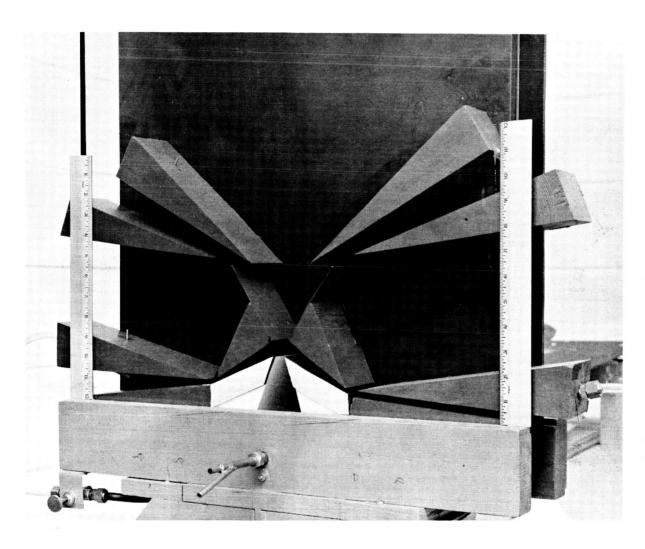


Figure 2-8. Three-State Model (Improved Design)

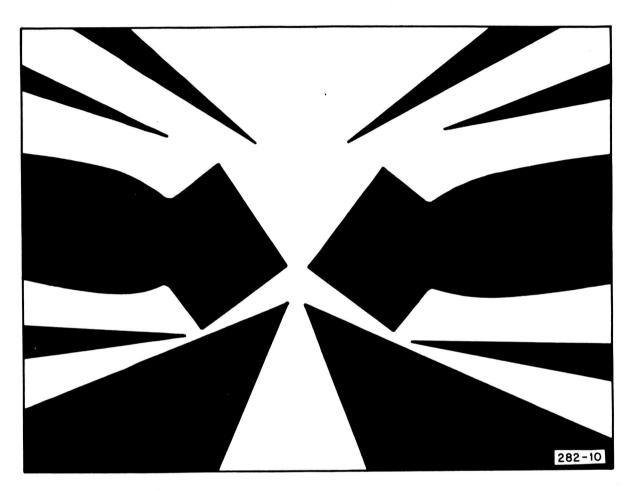


Figure 2-9. Magnified View of Adjustable Element

#### SECTION 3

#### THE EVOLUTION OF AN ANALYTICAL APPROACH TO FLUID SYSTEMS

#### 3-1. GENERAL

Application of a new idea rarely waits for the idea to be perfected. Pure fluid logic elements have far to go before anything like optimum designs are achieved, yet even in their present state they have found industrial uses as timing and control devices. Elements have been designed which use very little power, are quiet, and can operate on conventional shop air under almost any conditions of temperature, noise, vibration, humidity, and shock.

UNIVAC has built a timing device for the Sandia Corporation and a small computer for demonstration purposes by use of the UNIVAC pure fluid NOR gate. A paper announcing the UNIVAC Fluid Computer, the world's first pure fluid digital computer, has been presented at the Fall Joint Computer Conference in San Francisco this year, and it is anticipated that this significant paper will herald a new era in man's use of fluids.

At present many problems which can be solved by means of electromagnetic relays can be solved more cheaply and reliably by means of fluid amplifiers. UNIVAC expects to develop elements which are fast enough to do fairly sophisticated computer logic. These elements will be sufficiently inexpensive to justify the extended use of parallel logic in performing operations hitherto regarded as lying in the domain of electronics. Mechanical and electromechanical logic elements will become a rarity since they will, in general, be replaced by fluid devices. Hole, ripple, and bump detectors, such as those used in paper tape readers, will probably use air both as a means of detecting information and as the medium for pure fluid logic decoding and error detection circuits.

The chief difficulty so far has been the inability to predict the reliability of elements. Now that the advantages of low-gain multistate elements have been demonstrated there appears every reason to expect that digital and analog pure fluid systems will be increasingly in demand. They are immune to radiation and do not emit radio frequency signals which might be decoded, they have almost infinite life, and they can operate under extremes of temperature and pressure which would be destructive to any other known system.

Work carried out so far has indicated that as the number of stable conditions for a fluid element increase so do the geometric sensitivity, the power required, and the switching time. It appears also that these three factors increase with pressure gain and flow gain. Since the number of variables which enter into the design of a fluid element is large it is helpful to consider them independently and then to envolve an empirical relationship which will aid in the design of a pure fluid system.

#### 3-2. REYNOLDS NUMBER

There seems to be a minimum value below which an element will not perform satisfactorily. Elements designed to operate in the turbulent region fail at higher minimum Reynolds numbers than elements, such as the Auger turbulence amplifier, designed for transition between turbulent and laminar flow. This fact suggests that an element designed to operate entirely in the laminar region, while perhaps being capable of operating in the turbulent region, would perform best at much lower Reynolds numbers than elements in current use.

#### 3-3. FLOW GAIN

In order to fan out from one element to a number of similar elements when only one output is available, a flow gain of at least two must be provided. However, very high flow gains depend on an aerodynamic triggering action which is strongly dependent on Reynolds number unless the element is operating well in the turbulent regime. At very high Reynolds numbers  $\mathbf{R}_{\mathbf{e}}$  the flow gain  $\mathbf{G}_{\mathbf{f}}$  approaches an asymptotic value. At low Reynolds numbers the flow gain tends to become lower although this is not always the case.

#### 3-4. PRESSURE GAIN

If an element is used to drive a similar element some pressure gain must be provided to overcome line losses and any variability in the elements themselves. A passive element will not have gain; however, the loss across a passive element must be restored at the next active stage to guarantee propagation of a fluid signal. In general, passive elements perform combinational logic on two or more inputs while active elements perform amplification and inversion of a single input.

## 3-5. ASPECT RATIO

Essentially, two-dimensional elements are elements with large aspect ratios. Experiments have shown that an element can be considered to be two-dimensional if the depth of the power nozzle is at least five times the width. Unfortunately, high aspect ratios result in much waste of power, since for a given nozzle width the power required is proportional to the depth of the element. As the aspect ratio of the power nozzle approaches unity, secondary flows become significant, and the performance of the device changes. This suggests that there must be an optimum aspect ratio for minimum power when the cross-sectional area of the nozzle is kept constant and the performance characteristics are maintained by suitable changes in element geometry.

#### 3-6. FAN-OUT

The flow gain for an element is determined by the required fan-out. Since for operation at minimum Reynolds number the flow gain must be kept low, the fan-out should be kept to a minimum consistent with logical convenience. An amplifier providing both polarities of an input signal has an intrinsic gain of 2; therefore, if such an amplifier is used in a logical design there need be no dividing of the flow from any one output. Flow dividers have always been a source of difficulty, because at high frequencies dynamic coupling of the output legs can create spurious signals which cause errors. Another undesirable aspect of dividers is that they make necessary a reduction in the nozzle size of the passive elements and an increased dependence on flow isolators or bleeds to accommodate variations in the output loads resulting from different fan-out needs. A method of providing fan-out which overcomes the load variation difficulty is discussed in Appendix C,

but the nozzle size difficulty remains and may prove to be insurmountable when extremely small power supply nozzles are used.

#### 3-7. NUMBER OF STABLE STATES

Experience with the wall attraction and edgetone flip-flops has shown that two stable states are extremely difficult to obtain in a practical fluid logic element designed to operate at low Reynolds numbers. Work on multistable elements has revealed a compounding of the difficulties. Even when a workable multistable element design had been achieved, it was found to be extremely difficult to reproduce the elements. Dynamic tests showed that the switching time of these elements was even slower than that of two-state elements. It thus appears that there are both practical and theoretical objections to the use of elements with three or more stable states. Indeed, even the two-state flip-flop may be impractical at extremely low Reynolds numbers.

#### 3-8. POWER

The number of elements to be driven by each output of a fluid device affects the power which must be supplied to the element. Power gain is a second factor which must be considered since high gain results in a greater percentage of lost power than does low gain. In order to minimize the power consumed by an element it is clearly advantageous to keep the required power gain at the lowest practical level. Logical design studies have shown that any logical functions can be performed by active elements which have a fanin of two and a fan-out of two. If each output leg of an active element is used to drive only one element then the flow gain need be little more than unity and the pressure gain certainly no more than 2. This would allow for an ample margin of safety under all reasonable conditions.

### 3-9. SENSITIVITY TO VARIATIONS IN GEOMETRY

Tests carried out on an inverter and a flip-flop prior to work on multi-state elements showed that high gain can be achieved only if element geometry is held within extremely close tolerances. As the size of the element is reduced these tolerances become even more critical. This means that highly refined reproduction techniques are required for elements having gains comparable to those of their electronic counterparts.

#### 3-10. SUITABILITY FOR INTEGRATED CIRCUITRY

One of the chief advantages of fluid logic devices is their ability to be interconnected within a single piece of material in the form of a "sheet" of elements containing all power supplies, dumps, and passages. Such sheets of elements could form logic modules which could then be placed in a pile to form a complete fluid system perhaps incorporating both digital and analog fluid elements. Some of the high gain elements developed at UNIVAC had production yields as high as 95 percent when they were injection-molded. Ordinarily this would be perfectly acceptable, but when 100 of these elements are molded simultaneously into a single logic module the yield of these modules would become a mere  $(0.95)100 \times 100$  or 0.59 percent, which would be extremely wasteful. Elements with low gain can have much higher yields, and it now appears quite feasible that working modules consisting of several hundred elements each could be injection-molded while still producing a yield close to 100 percent.

#### 3-11. SWITCHING SPEEDS

Since digital logic relies essentially on counting bits, it is highly desirable to count rapidly; otherwise, the time required for performing useful calculations might be unacceptably long. Unlike analog fluid devices whose response is faster than that of most mechanical systems they are required to control, digital devices must perform many cycles to effect even a simple control operation where accuracies better than those obtainable from analog devices are required. It is therefore vital that pure fluid digital devices be as fast as possible. Experiments have shown that multistate elements and elements designed to have high gains are at least an order of magnitude slower than elements designed to have modest gains. The important parameter here is the degree of dependence on wall attraction. The lower the gain of an element, the less need be the dependence on wall effects. For a flow gain of unity with a pressure gain of 2 it seems that wall effects become unnecessary. Under these conditions an element switches in a time compatible with the molecular transport time of the fluid travelling from the power nozzle to the receiver. Calculations have shown that these times can be in the order of ten microseconds.

### 3-12. PROPOSED EMPIRICAL RELATIONSHIPS

#### 1. Minimum Reynolds number

$$R = K_{i} a_{i}^{(N-1)} F^{b}_{i} G^{c}_{i} (1+H^{-d}_{i})$$
 (1)

Where

is the minimum Reynolds number R  $K_i$   $a_i$   $b_i$   $c_i$   $d_i$ positive empirical constants suffix i refers to the class of element i = 1laminar flow device device operating in both turbulent and laminar i = 2regions, for example, the turbulence amplifier turbulent flow device, for example, the early i = 3DOFL-type flip-flop is the number of stable states N is the flow gain G is the pressure gain

The Reynolds number is based on the definition  $\frac{vd}{v}$  where v is the mean velocity of the fluid issuing from the power nozzle, d is the width of the power nozzle, and v is the kinematic viscosity of the fluid.

is the aspect ratio of the power nozzle

# 2. Sensitivity to Variations in Geometry

$$S = C_i R^{d_i}$$
 (2)

where

Н

S is the sensitivity to geometric variations, and  $\mathbf{C}_{\mathbf{i}}$  and  $\mathbf{d}_{\mathbf{i}}$  are empirical constants.

The sensitivity S is defined as  $\frac{h}{d}$  where h is the minimum distance the most sensitive portion of the element can move from one extreme to the other while maintaining satisfactory performance and d is the power nozzle width.

#### 3. Minimum Switching Time

$$t = \frac{\ell}{v} (1 + C_i R^{e_i}) \tag{3}$$

where

t is the minimum switching time

 $\boldsymbol{c}_i$  and  $\boldsymbol{e}_i$  are positive empirical constants

 $\ell$  is the distance from the power nozzle to the receiver

v is the mean velocity of the fluid issuing from the nozzle

## 3-13. DETERMINATION OF MINIMUM POWER REQUIRED PER ELEMENT

Once the requirements of switching time have been met it is possible to obtain the power requirement by use of the theoretical relationship

$$P = pQ$$

where P is the power, p the total gauge pressure at the supply nozzle, and Q the rate of discharge.

Now discharge rate = nozzle area × mean velocity at nozzle exit

$$= d^{2}Hv$$

$$= d^{2}H\sqrt{\frac{2p}{\rho}}$$
(4)

Therefore, P

$$= d^2 H \sqrt{\frac{2}{\rho} p^2}$$

### 3-14. DESIGNING A FLUID SYSTEM

We are now in a position to lay down the rules for designing a digital fluid system. First, it appears from the empirical formulae that elements

with the least possible gain and the least number of stable states should be used. In the absence of experimentally obtained values for the empirical constants it is necessary to determine experimentally the lowest permissible Reynolds number for a low gain device. At the same time it is possible to carry out a logical design study employing the element to be used in the system and hence to obtain the maximum permissible switching time. In order to determine the size of the element that is necessary for achieving the specified switching time at the lowest permissible Reynolds number, it is necessary to express the switching time of the element as a function of the fluid velocity and the nozzle width. This may be done by obtaining the switching speed of the experimental element by measuring the frequency of an oscillator built from a number of such elements and then obtaining the Strouhal number S in the formula.

$$S = \frac{Tv}{d} \tag{5}$$

Where

T is the switching time

v is the supply nozzle velocity

d is the supply nozzle width

Thus, knowing that the minimum Reynolds number R is given by

$$\mathbf{R} = \frac{\mathrm{vd}}{\mathrm{v}} \tag{6}$$

we may determine the values of v and d by solving equations (5) and (6) simultaneously:

Let  $T_1$  be the required switching time, then

$$\left(\frac{S}{T_1}\right) = \frac{v}{d} \tag{7}$$

$$(\mathbf{R}v) = \mathbf{v}\mathbf{d} \tag{8}$$

therefore

$$d^2 = \frac{RvT_1}{S} \tag{9}$$

therefore

$$d = \sqrt{\frac{RvT_1}{S}}$$
 (10)

Equation (10) gives the maximum nozzle width consistent with minimum power and the required switching time. If the resulting nozzle width is too large it is permissible to reduce the size of the element; however, this will result in an unnecessarily fast element.

Let us assume that the nozzle width d is too large for the size limitations of the system being designed. We shall assume that the required nozzle width is d; then for Reynolds number to remain constant, we have

$$R = \frac{v_1 \cdot d_1}{v}$$

therefore

$$v_1 = \frac{Rv}{d_1} \tag{11}$$

$$v_1 = v \cdot \frac{d}{d_1}$$

The new total gauge  $p_1$  is given by

$$p_1 = \frac{1}{2} \rho v_1^2$$

$$=\frac{1}{2}\rho\left(\mathbf{v}\cdot\frac{\mathbf{d}}{\mathbf{d}_{1}}\right)^{2}\tag{12}$$

$$p_1 = \left(\frac{d}{d_1}\right)^2 p$$

Therefore, the new power required for the smaller element is 'given by

$$P_{1} = d_{1}^{2} H \sqrt{\frac{2}{\rho}} p_{1}^{\frac{3}{2}}$$

$$= d_{1}^{2} H \sqrt{\frac{2}{\rho}} (\frac{d}{d_{1}})^{3} p^{\frac{3}{2}}$$

$$= (\frac{d}{d_{1}}) d^{2} H \sqrt{\frac{2}{\rho}} p^{\frac{3}{2}}$$
(13)

therefore

$$P_1 = \frac{d}{d_1} P$$

Thus, the power required varies inversely with the size of the elements, so that to achieve minimum power it is necessary to use the largest nozzle consistent with the longest permissible switching time.

So far we have assumed that the fluid used was to be of specified viscosity and density. Let us now assume that the density of the fluid, varies in proportion to the absolute pressure, while the viscosity remains sensibly constant.

Let the new density be  $\rho_{\mbox{\scriptsize 2}};$  then from equation (10) the new nozzle width  $d_2$  is given by

$$d_{2} = \sqrt{\frac{Rv_{2}T_{1}}{S}}$$

$$= \sqrt{\frac{R\mu T_{1}}{\rho_{2}S}}$$

$$= \sqrt{\frac{\rho}{\rho_{2}}} d$$
(14)

Thus, the size of the element varies inversely as the square root of the density. It therefore follows that if calculations for a fluid system which uses air showed that the required nozzle width was too small to be practical, then larger elements could be used with air as the working fluid; however, to keep the power required to a minimum, it would be necessary to reduce the ambient pressure. This would necessitate a sealed system.

The use of sealed systems has other advantages besides permitting operation at reduced pressures:

- 1. Sealed systems are impervious to atmospheric variations.
- They permit the use of a variety of gasses and liquids, depending on the specified requirements.
- 3. They permit a high degree of purity and freedom from particles in the working fluid.

We shall now determine what parameter governs the choice of an ideal working fluid when the switching time is specified and minimum power is to be used. Equation (4) gives the power required by an element in terms of nozzle size, the fluid density, and the power supply differential pressure:

$$P = d^2 H \sqrt{\frac{2}{p}} p^{\frac{3}{2}}$$

Now  $p = \frac{1}{2}\rho v^2$  but from equations (7) and (8)

$$v^2 = \frac{SRv}{T_1}$$

therefore

$$p = \frac{1}{2}\rho \left(\frac{SRv}{T_1}\right)$$

$$= \frac{1}{2} \frac{SR\mu}{T_1}$$

also from equations (7) and (8)

$$d^2 = \frac{RvT_1}{S}$$

therefore the power may be expressed as

$$P = \frac{R\mu T_{1}}{\rho S} H \sqrt{\frac{2}{\rho}} \left(\frac{1}{2} \frac{SR\mu}{T_{1}}\right)^{\frac{3}{2}}$$

$$= K \sqrt{\frac{\mu^{5}}{\rho^{3}}} = K \sqrt{\vartheta^{3}\mu^{2}}$$
(15)

where K is a constant.

Thus, the ideal fluid is one for which the product  $\upsilon^3\mu^2$  is least. We may nondimensionalize this value by comparing fluids with air

Specific dynamic viscosity = 
$$\frac{v^3 \mu^2}{v_a^3 \mu_a^2}$$

where  $\upsilon_{a}$  and  $\mu_{a}$  are, respectively, the kinematic and absolute viscosities of air.

#### 3-15. THE EFFECT OF SONIC PROPAGATION VELOCITY

If the switching time of an element is long compared with the time taken for a sonic pulse to travel along the interconnecting passages, then incompressible theory may be used to determine the impedance of the fluid in each passage by treating the impedance as a lumped mass. On the other hand, if the switching time is short then lumped parameters can no longer be used, and all interconnecting passages must be properly impedance-matched in order to avoid the danger of unwanted transients. This is a study in itself, and no attempt will be made to cover it in this report.

#### SECTION 4

#### LOGIC AND ALGEBRA STUDIES

The limitations of a multistate fluid logic element have placed emphasis on the fundamental nature of binary logic. Even the three-state memory element operates only on binary signals, and there seems little point in developing algebra for which no fluid logic elements exist. We shall therefore confine ourselves to logic studies based only on those multistate fluid logic elements which showed reasonable promise.

#### 4-1. DESCRIPTION OF THREE MULTISTATE ELEMENTS

#### 1. The Tristable Memory Element

Figure 4-1 shows the tristable memory element, which has the following characteristics. There is no output unless the power input  $\mathbf{C_i}$  is present.

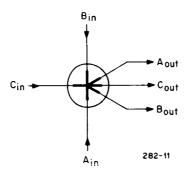


Figure 4-1. Three-State Memory Element

If  $C_i$  is present, the output is a function of the deflecting inputs  $A_i$  and  $B_i$ . The outputs are undefined for the case when both deflecting signals are present; therefore,  $A_i$  and  $B_i$  must be mutually exclusive. The outputs at a time t may be expressed by the following equations:

$$\mathbf{A_{o_t}} = \mathbf{C_{i_t}} [\mathbf{C_{o_{t-1}}} \ \mathbf{A_{i_{t-1}}} \ \overline{\mathbf{B_{i_{t-1}}}} + \mathbf{A_{o_{t-1}}}]$$

$$B_{o_t} = C_{i_t} [C_{o_{t-1}} B_{i_{t-1}} \overline{A_{i_{t-1}}} + B_{o_{t-1}}]$$

$$C_{0_t} = C_{i_t} \overline{A_{i_{t-1}}} \overline{B_{i_{t-1}}} [C_{0_{t-1}} + \overline{C_{i_{t-1}}}]$$

To change the state of the element, it is necessary to drive  $C_i$  off momentarily. When the power comes back on, it will give output  $C_0$  unless  $A_i$  or  $B_i$  is present. One can, however, switch from the  $C_0$  state to either the  $A_0$  or  $B_0$  state by applying an  $A_i$  or  $B_i$  control pulse without turning off  $C_i$ .

# 2. The 2-3 Element

The 2-3 gate, which is illustrated in Figure 4-2, is a two-input, three-output passive element. It performs the logic function of the three conventional passive AND gates shown in Figure 4-3. Although this element is no

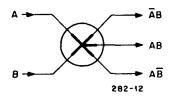


Figure 4-2. Two-Input,
Three-Output (2-3) Passive Element

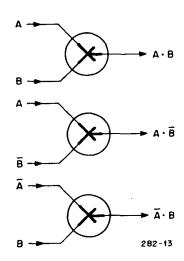


Figure 4-3. Passive AND Gates Equivalent to a 2-3 Element

faster than the two-input gate, it has the following advantages, where applicable:

- A. Reduces the number of elements needed
- B. Lowers the power requirements of the driving elements

#### 3. The 3-5 Element

Figure 4-4 shows the three-input, five-output passive element. The center output produces an ambiguous signal and will not be considered here.

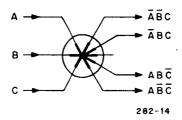


Figure 4-4. Three-Input, Five-Output 3-5 Passive Element

Logically, the 3-5 element performs the same function as the 4 three-input passive AND gates shown in Figure 4-5. For three binary inputs there are

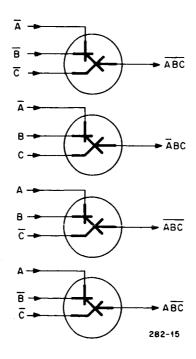


Figure 4-5. Passive AND Gates Equivalent to a 3-5 Element

eight possible combinations. Using conventional circuits, 8 three-input gates would be needed to decode three binary bits. Since the 3-5 element replaces four conventional gates, it will be shown that two such elements are needed to completely decode three binary bits.

#### 4-2. SOME APPLICATIONS OF MULTISTATE ELEMENTS

#### 1. The Queueing Register

This register involves the use of the three-state memory element. One of the functions of the queueing register is to accept information presented to it serially and to store the information so that it may be read either parallely or serially. When being read serially the information is unloaded from its output end one bit at a time. A shift signal is applied at this end as each bit of information is read, and the whole word drops one place. This procedure continues until the last bit in the word has been read and the register is left empty. A new word may then be read in serially. As each bit is presented to the input end of the register, it "drops" to the last empty space nearest the output end, and thus the order of the bits is maintained. For this reason the queueing register is sometimes called a bit tube.

The requirements for a queueing register are as follows:

- A. A storage element capable of holding and transmitting data.
- B. Control logic for each cell to indicate its status, that is, full or empty.

The queueing register is not controlled by a sprocket or shift pulse. It can be loaded at a rate determined only by the switching time of the components. Control for this register is achieved by means of a third state for each storage element, that is, besides a binary one state and a binary zero state, each storage element must appear to be in an empty or no data state before it has received data or after it has transmitted data.

A block diagram of two cells in a queueing register is shown in Figure 4-6. Each cell comprises an input stage and an output stage, where each stage has three inputs and three outputs. The logical rules governing the operation of both the input and output stages are identical. Figure 4-7 shows a single stage of a queueing register. The input and output signals signify the following:

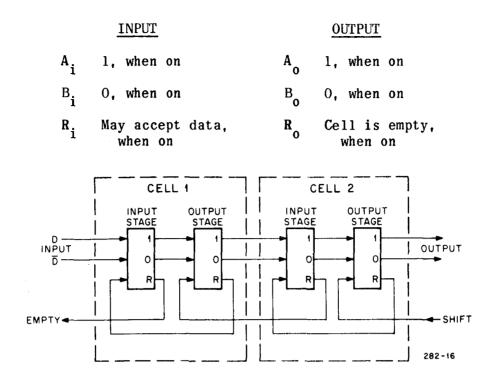


Figure 4-6. Two Cells of a Queueing Register

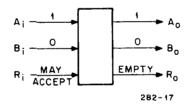


Figure 4-7. Single Stage of a Queueing Register

The logical rules governing the relationship between the inputs and the outputs of each stage are as follows:

- A. Only one output can be ON at a given instant.
- B. One of the three outputs must always be ON.
- C. If the input signal  $R_{\dot{1}}$  is ON then any one of the output signals can be ON, depending on the previous condition of the other two input signals.
- D. If  $R_i$  is turned ON while both  $A_i$  and  $B_i$  inputs are OFF, then  $R_0$  will stay ON.

- E. A pulse applied to the  $A_i$  input while  $R_0$  is ON will turn on the  $A_0$  output and simultaneously turn OFF  $R_0$ . Similarly a pulse applied to the  $B_i$  input while  $R_0$  is ON will turn on the  $B_0$  output and simultaneously turn OFF  $R_0$ .
- F. If  $R_i$  is turned ON while the  $A_i$  input is ON, the  $A_o$  output will immediately turn ON and  $R_o$  will turn OFF.
- G. If  $R_i$  is OFF then  $R_o$  will be ON irrespective of the condition of inputs  $A_i$  and  $B_i$ .
- H. If  $R_0$  is OFF the state of the outputs  $A_0$  and  $B_0$  cannot be changed by means of signals applied to either input  $A_i$  or  $B_i$ ; the state of  $A_0$  and  $B_0$  can only be changed by pulsing OFF  $R_i$ .

These rules may be expressed by means of the following formulae:

$$A_{o_{t}} = R_{i_{t}} \left[ A_{i_{t}} \overline{B_{o_{t-1}}} + A_{i_{t-1}} \overline{R_{i_{t-1}}} \right]$$

$$B_{o_{t}} = R_{i_{t}} \left[ B_{i_{t}} \overline{A_{o_{t-1}}} + B_{i_{t-1}} \overline{R_{i_{t-1}}} \right]$$

$$R_{o_{t}} = \overline{R_{i_{t}}} + R_{o_{t-1}} \left[ A_{i_{t}} B_{i_{t}} + \overline{A_{i_{t}}} \overline{B_{i_{t}}} \right]$$

In specific design situations which make use of conventional elements, it is usually cheaper to control a register by means of clock pulses than to add a third state to each cell. This is not the case in fluid circuits, however. The tristate element is no more expensive than a flip-flop, and the basic cell of a queueing register is no more expensive than that of a shift register which employs a clock to synchronize the shifting of bits.

Two cells of an asynchronous queueing register are shown in detail in Figure 4-8. Each cell requires two stages: an input stage 1 to receive data from the preceding output cell and an output stage 2 to transmit data to the following cell. For a cell to be able to receive data, its output stage must be empty; this means that both the 1 and 0 outputs must be OFF. Then its output amplifier 3 is ON and supplies power to the input stage 1. When the input stage is activated, it will switch to its 1 or 0 state only if the preceding output stage is full, that is, either the 1 or the 0 output of cell 1 is high. Figure 4-9 shows a segment of an actual queueing register circuit.

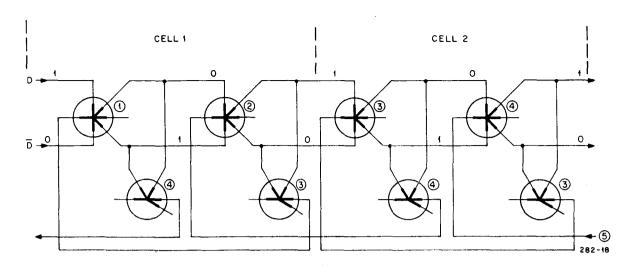


Figure 4-8. Two Cells of A Queueing Register Using Fluid Elements

The following example will illustrate the operation of the queueing register: The register is initially empty, both 1 and 0 outputs being OFF. When no data are presented to the input stage, lines D and  $\overline{D}$  remain OFF. When either D or  $\overline{D}$  is pulsed the input stage (1) of cell 1 is switched. output stage (2) of cell 1 will now be switched. When one of the output lines of cell 1 turns ON, its output amplifier (3) will turn OFF and thereby deactivate the input stage. Next, the input stage of cell 2 is switched. This turns OFF its output amplifier (4) and thus deactivates the cell 1 output stage (2). Since the output stage of cell 1 is now empty, its output amplifier (3) will turn ON and allow the input stage to receive data. When the output of cell 2 is switched, its input stage will be turned OFF. This will activate the output stage of cell 1. A bit of data has been shifted to the output stage of cell 2, which is now full and can receive no more data until emptied by means of a shift pulse applied at (5). Cell 1 is ready to receive data and will store the data until cell 2 has been emptied. In this manner, the data "falls" to the last empty cell in the register. As the data are taken from the output cell, the queue of bits moves up one cell at a time until all the data have been used and the register is empty again.

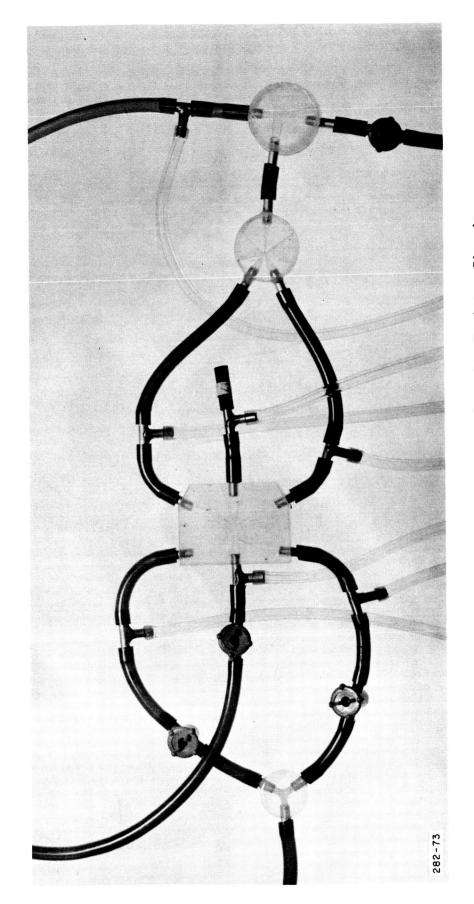


Figure 4-9. Section of an Actual Queueing Register Circuit

# 2. The Full Adder

## A. Using the 2-3 Element

Figure 4-10 shows a full adder circuit designed with conventional AND gates and amplifiers. The first stage of the adder forms the sum  $\mathbf{S}_1$  of two binary bits A and B. A third input  $\mathbf{C}_{in}$  is then added to this output to

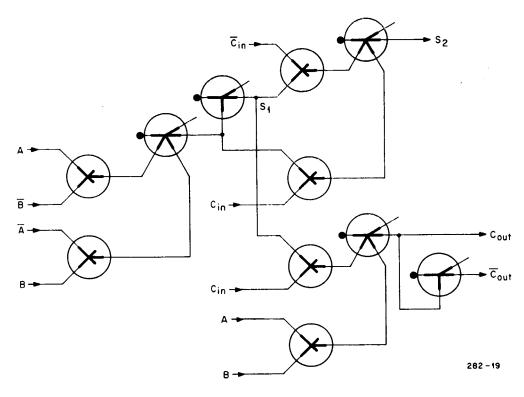


Figure 4-10. Full Adder Circuit Using Conventional Elements

form the final sum  $\mathbf{S}_2$ . The logical functions may be expressed as follows:

$$S_{1} = A\overline{B} + \overline{A}B$$

$$S_{2} = S_{1} \cdot \overline{C}_{in} + \overline{S}_{1} \cdot C_{in}$$

$$C_{out} = A \cdot B + S_{1} \cdot C_{in}$$

 ${
m C}_{
m out}$  is the carry to the next higher bit position. Both polarities of  ${
m C}_{
m out}$  are generated, since they will be needed to form the sum and carry of the next stage.

Figure 4-11 is a diagram of a full adder using the 2-3 gate. Figure 4-12 shows the actual full adder in which the 3-5 elements, discussed under 2B below, are used as 2-3 elements. This adder produces the sum in the same time as the conventional adder. However, only one polarity of  $\mathbf{C}_{\text{out}}$  is needed. Also the 2-3 adder uses four less elements per stage than the conventional adder. The input drive requirements are less by a factor of one-third.

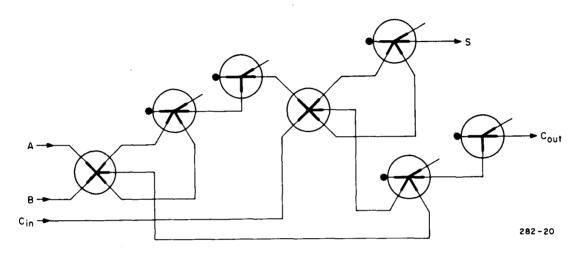


Figure 4-11. Diagram of a Full Adder Circuit With 2-3 Elements

### B. Using the 3-5 Element

Figure 4-13 is a diagram of a full adder which uses the 3-5 gate and conventional NOR elements. Figure 4-14 shows the actual full adder in which the 3-5 elements are used. Only four elements and six input drives are required. If only conventional NOR elements are used, as shown in Figure 4-15, nine elements and 18 input drives are needed. There is also a speed advantage, since a level of NOR elements is replaced by the faster 3-5 passive elements. The 3-5 element also has applications in addressing or selection logic. It is useful whenever more than one logical function of three inputs is required.

Up to this point it has been assumed that NOR gates would be used in gating the outputs from the multistate elements. The NOR gate uses only one of two available output legs and is therefore much more wasteful of available output signals than it need be. In order to demonstrate the full power of multistate logic elements it was necessary to develop a dual-output amplifier. With this element it was possible to simplify the design of the

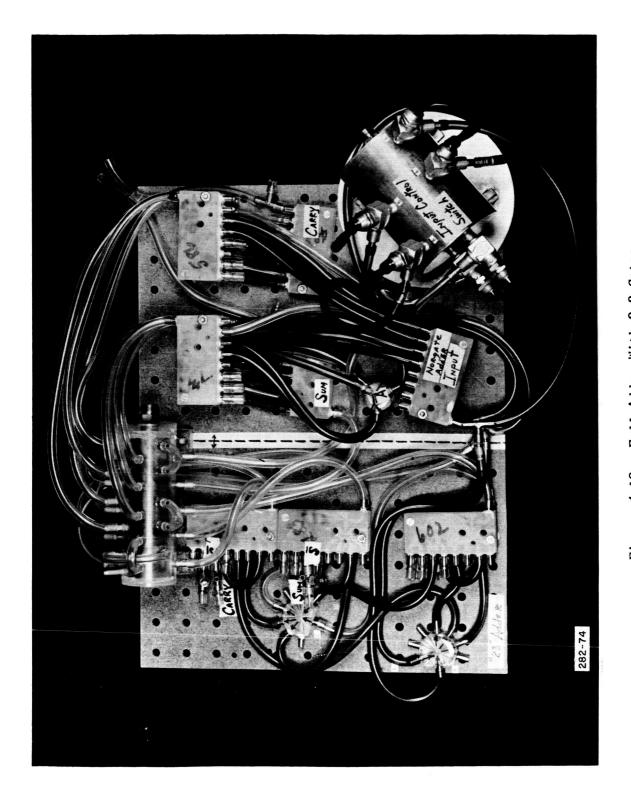


Figure 4-12. Full Adder With 2-3 Gates

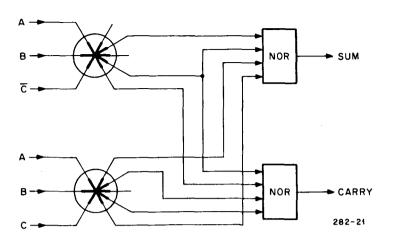


Figure 4-13. Diagram of a Full Adder With 3-5 Gates

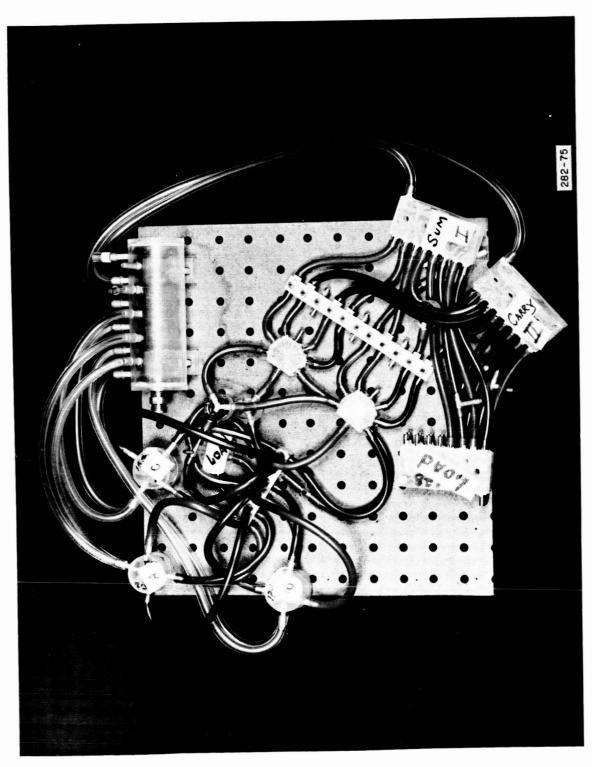
full adder shown in Figure 4-11 so that it would appear as shown in Figure 4-16.

Extensive use of this adder has been made in the design of the demonstration arithmetic unit, which will be described in Appendix A.

## 3. The Flip-Flop

A flip-flop has been designed by use of the two-output inverter/amplifier and a 2-3 element. The design of this element is shown in Figure 4-17a. For purposes of comparison a conventional fluid flip-flop is shown in Figure 4-17b. When only one of the inputs is pulsed the mode of operation of the two elements is identical. However, if both  $A_i$  and  $B_i$  are held on, the flip-flop shown in Figure 4-17b behaves unpredictably, whereas the flip-flop shown in Figure 4-17a has a predictable output state.

The operation of the new flip-flop is as follows: Element 1 is a two-input amplifier/inverter which can be held in the  $B_0$  state by means of a continuous pressure signal applied at either of its two inputs. Thus, when a continuous pressure is applied at  $B_i$  the output flow will always be from  $B_0$  irrespective of the state of  $A_i$ . The 2-3 multioutput element 1 permits the output 1 to feed back to one of the inputs of amplifier/inverter 1, provided 1 is off, so that the 1 state can be maintained by pulsing 1 only. A pulse applied to 1 will restore the output to 1 unless a signal 1 is present. If input 1 is held on then the flip-flop behaves as a conventional amplifier/inverter whose state depends on 1 only.



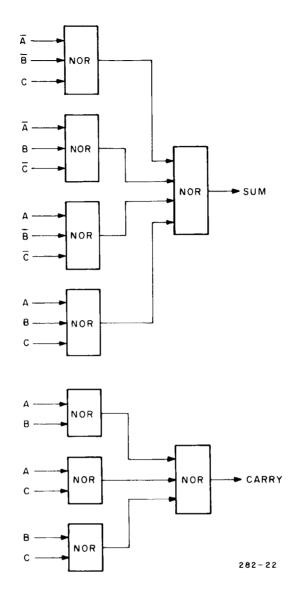


Figure 4-15. Full Adder Using NOR Gates Only

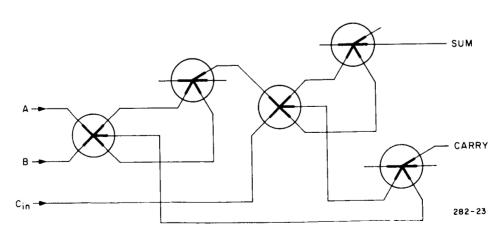


Figure 4-16. Full Adder Using Dual-Output Amplifier and 2-3 Elements

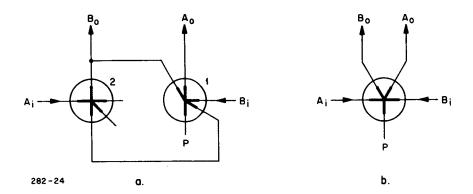


Figure 4-17. Two Different Flip-Flops

The outputs at a time t for the two types of flip-flop may be expressed by the following equations:

Flip-flop (Figure 4-17a)

$$A_{0_{t}} = \overline{B_{i_{t}}} \left[ A_{0_{t-1}} + A_{i_{t}} \right]$$
 (16)

$$B_{0_{t}} = \overline{A_{i_{t}}} B_{0_{t-1}} + B_{i_{t}}$$
 (17)

with no input restrictions.

Flip-flop (Figure 4-17b)

$$A_{o_{t}} = \overline{B_{i_{t}}} \left[ A_{o_{t-1}} + A_{i_{t}} \right]$$
 (18)

$$B_{0_{t}} = \overline{A_{i_{t}}} \left[B_{0_{t-1}} + B_{i_{t}}\right]$$
 (19)

subject to the input restriction:

$$A_{i_t} B_{i_t} = 0$$

It will be noted that the  $B_{0t}$  output (2) for the flip-flop shown in Figure 4-17a may be obtained simply by removing the parentheses from equation (19).

#### 4-3. ASYNCHRONOUS LOGIC

Asynchronous logic is comprised of a multiplicity of partially independent yet interrelated logic subnets. The mechanization of the subnets may utilize self-clocking or a combination of self-clocking and a reference clock. The essential distinction is made by the fact that the subnets are time-interdependent only during the interchange of data resulting from completed macro-operations but need not have a common timing reference in performing their particular micro-operations. With a system of logic of any complexity there exists hierarchies of asynchronism. The purpose of this discussion, however, is to discuss, on the microscopic scale, the self-clocked logic which forms the keystone of the asynchronous system.

In logic nets employing a reference clock the time for execution of a micro-operation is rigidly fixed by the clock interval. The absolute response time of any given logic net is in general dependent on the content of the data upon which it is acting, but the reference clock must provide an interval greater than the worst-case maximum of any net which it is controlling. In contrast, the response time of a self-clocked net is limited only by its own speed and that of the other nets from which it is receiving data or to which it is transferring data. The self-clock elements are thus synchronized during, and in actuality, by the exchange of data.

The most basic self-clocked net must be capable of:

- Indicating a ready or a busy condition as regards communication with an associate element to receive new data and providing acknowledgement to the transmitting element when data have been received.
- 2. Storing a result until conditions permit its transfer into an associate element.
- Transferring a result in response to a ready condition in a receivaing element and then clearing itself to the ready condition upon acknowledgement by the receiving element.

It can be seen from this that a self-clocked element handling binary data must be a ternary element capable of recognizing and indicating three states: 1, 0, and nil.

#### 4-4. THE BIQUINARY SYSTEM

Many ways exist for representing numbers. Earliest man recorded numbers by drawing a set of strokes, making notches on a stick, or using pebbles;

the number of strokes, notches, or pebbles used corresponded to the number he wished to represent. As it became necessary to deal with larger and larger numbers this process became cumbersome, and so early man, notably the Egyptians, invented special symbols to represent the larger groups of strokes. These symbols were linked together in additive-substractive combinations, and traces of such a number system survive today in Roman numbers.

Even this improvement, important as it was, required an indefinite number of higher and higher value different symbols to represent very large numbers if the expression was not to become burdensomely long, and clearly a better method was needed. This method was supplied by the Sumerians about 2100 BC in what is regarded by some as the greatest invention of all time: positional notation.

The Sumerians used only a finite number of different symbols to represent any number, but the <u>value</u> of a symbol depended on its position in the number in a clear and simple fashion. Thus, the collection of symbols [5, 6, 3] in Sumerian notation meant  $5 \times 60^2 + 6 \times 60 + 3$  (which equals 18,363 in our notation). In other words, the Sumerians were using the base 60, just as we use the base 10. One can only speculate as to why they chose 60 as a base (the large number of factors perhaps?) but it is interesting to note the slight survival of this base in our measurement of time and in the division of the circle.

Any integer may be used as a base, or, as it is more properly called,  $\underline{radix}$ , in a positional system, and we commonly use the radix 10 and thus require symbols for the numbers 0 through 9. In the decimal system 4643 means  $4 \times 10^3 + 6 \times 10^2 + 4 \times 10^1 + 3 \times 10^0$ . Note that the symbol 4 has two different values, depending on its position. As stated before, any other integer could be used for the radix, and the value of a number expressed to the radix r is given by

$$\mathbf{N} = \sum_{\mathbf{j}} \mathbf{a}_{\mathbf{j}} \mathbf{r}^{\mathbf{j}}$$

where the coefficient  $\underline{a}$  may range from 0 to r-1. The radix 2 is often used in scientific work, and in this case the coefficient  $\underline{a}$  can only have the values 0 and 1.

What is not widely realized is that numbers can also be represented in a <u>mixed radix</u> system, where different positions use different radices, provided certain simple rules are followed. In a mixed radix system we could say

$$N = \sum_{j} a_{j} w_{j}$$

where  $w_j$  is the <u>weight</u> associated with the  $j^{th}$  position. A mixed radix system will be <u>compact</u> (no gaps, that is, every number is expressible) and <u>unique</u> (only one representation for a given number) if the weight  $w_j$  of a given position is given by the product of the radices of all positions to the right (the coefficients  $a_j$  of a given position are permitted to range from 0 to  $r_j$  - 1, where  $r_j$  is the radix of the position) and if the weight of the first or least significant position is unity. As an example, if the radices of a four-position number,  $a_3a_2a_1a_0$ , are, respectively,  $r_3$ ,  $r_2$ ,  $r_1$ ,  $r_0$ , then the value of the number is

$$N = a_3 r_2 r_1 r_0 + a_2 r_1 r_0 + a_1 r_0 + a_0$$

with the understanding that

 $a_3$  lies between 0 and  $r_3$  - 1

 $\mathbf{a}_2$  lies between 0 and  $\mathbf{r}_2$  - 1

 $a_1$  lies between 0 and  $r_1$  - 1

 $a_0$  lies between 0 and  $r_0$  - 1

Note carefully that if the radixes are all identical (r) the above expression for N becomes simply  $a_3r^3 + a_2r^2 + a_1r + a_0$ , the same as was given previously for a fixed radix system.

One particular mixed radix system is of some importance in computer work: this is the biquinary system. Starting with the least significant position the radices are, ... 5, 2, 5, 2, 5. In this system the natural numbers are:

0 = 00	10 = 100
1 = 01	11 = 101
2 = 02	12 = 102
3 = 03	13 = 103
4 = 04	14 = 104
5 = 10	15 = 110
6 = 11	16 = 111
7 = 12	17 = 112
8 = 13	18 = 113
9 = 14	19 = 114

21 would be 201; 45 would be 410; 57 would be 1012; 97 would be 1412. The weights of the respective positions are of course 1, 5, 10, 50, ..., .

Note from the table that the "quinary" part of 4 is the same as the "quinary" part of 9, that 4+4=8 and 9+9=18, and that both these numbers are equivalent with respect to modulo 5. It is this property of the biquinary system that makes it interesting for computer work. For one thing conversion to and from the decimal system becomes very simple; for another, a method of addition, sometimes called "function table" addition, which has some advantages to be described in a moment, becomes reasonable.

Computers which work in the decimal system do so by representing each decimal digit by a group of binary digits, or bits. Addition is one of the most important operations in a computer, and in a "decimal" computer each group of bits representing a decimal digit is sent to an adder network either serially, group by group, to one adder, or in parallel to many adders. The machine does not know that 2+2=4; it must figure it out each time. Adder networks are relatively complex and relatively slow.

A human learns in his early youth an addition table which consists of a set of 10 by 10, or 100, entires. In adding, say, 3+4, the human need not derive the result but "looks it up" in his memory. A machine could do the same thing, but storage and acquisition problems involved in a 100-entry table are not trivial. However, if numbers are represented in the biquinary system the machine need only store a five-by-five table (25 entries) and a two-by-two table. Thus, the amount of storage is reduced by a factor of almost 4. These two small tables, plus a few simple logic rules, could enable a machine to "look up" sums as a human does rather than compute them. In some types of computers, depending upon the machine philosophy and logic organization, this "function table" addition may be speedier than conventional addition. A notable example of a machine using both the biquinary system and

functional table addition is the very successful UNIVAC Solid State Computer. It is also interesting to note that the abacus, so widely and efficiently used in the Orient, is a biquinary device.

#### SECTION 5

#### A THEORETICAL FOUNDATION FOR FLUID LOGIC ELEMENTS

## 5-1. TRENDS IN FLUID DIGITAL LOGIC

At the start of these investigations it was expected that there would be optimizing criteria which would govern the fan-out and gain requirements for fluid elements. Our studies have shown that the optimum gain, fan-out, and number of stable states are "as low as possible." With this criterion in mind let us explore a few of the logical design implications which would result from carrying this idea to its logical conclusion.

The minimum fan-out which can be used in building a digital system is two. If the element being designed has two output channels, then each of these channels need drive only one element. Fan-in may be accomplished most readily by allowing two control signals to interact, as in the 2-3 element and the 2-2 element, or by permitting two independent control jets to supply flow to a common receiver, as in the OR gate. Thus, it appears that we have a family of at least three passive elements and one active element.

In order to minimize both pressure gain and flow gain it is necessary to ensure that each passive element be driven by an active element.

The elements shown in Figure 5-1 represent a group of basic elements which would permit any digital logic function to be accomplished. By use of only elements shown in Figure 5-1a and 5-1d, it would be possible to design any logic system by alternating the OR gate and the dual-output amplifier. The gate (b) is useful in performing AND and exclusive OR functions while providing some effective fan-out. The 2-2 element (c) may be used when cascading AND functions to provide a passive multiinput gate or to fan out rapidly when no intermediate logic is required. Thus the 2-2 element (c) may be used as a passive element when fanning in or as an active element when fanning out.

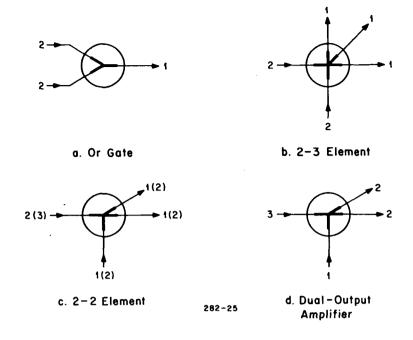
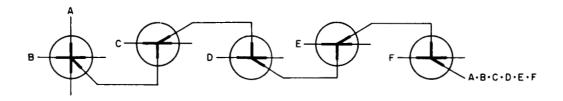


Figure 5-1. Four Low-Gain Elements

The numbers assigned to the inputs and outputs of these elements refer to the levels of pressure which should be supplied to the inputs and which will be available from the outputs. It will be noted that only three levels of pressure are used: Level 3 is the power supply level and is always present while the system is in operation, level 2 is the output from an active element, and level 1 is the output from a passive element.

Figure 5-2 shows two applications for the 2-2 element. Figure 5-2a shows the element being used as a passive gate. The object of this gate is to AND a number of inputs without the need for any power supplies. Figure 5-2b shows the element performing a simple fan-out function. In this case one additional power supply is required for each added output.

Figure 5-3 shows three additional multistate elements which could be used to reduce complexity of the logical design for certain applications. For example (a) has been used as a turn-OFF element for the outputs of a flip-flop in the arithmetic unit, which is discussed in Appendix A. Figure 5-3b may be used as a passive element for fan-in functions or as an active element for fan-out functions in a similar manner to that of Figure 5-1c. Figure 5-3c is primarily an amplifier and inverter. It may be used in place of the dual-output amplifier shown in Figure 5-1d and may offer logical advantages in some instances.



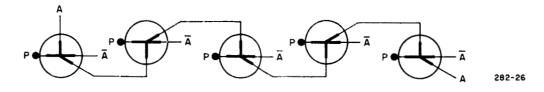


Figure 5-2. Fan-In and Fan-Out Circuits

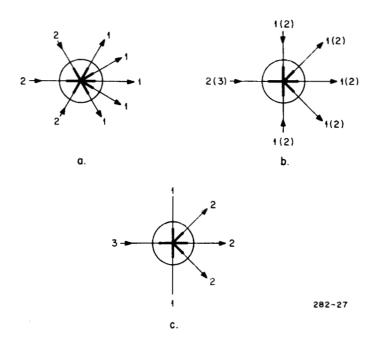


Figure 5-3. Three Multistate, Non-Memory Logic Elements

It should be noted that none of these elements relies on wall lock-on effects. Essentially they are all momentum-type or jet-reaction-type elements and may therefore be adapted for use either as digital or as analog elements. Their advantages are fast response, simple design, and efficiency over a wide range of Reynolds numbers.

### 5-2. TRENDS IN FLUID ELEMENT DESIGN

The three main requirements which digital fluid logic elements must satisfy are low power, high speed, and insensitivity to small geometric variations. Low power places a premium on low aspect ratio and demands that elements be capable of operating at low Reynolds numbers. High speed demands that elements be extremely small and that phenomena which depend on the building up or breaking down of boundary layers or on the creation and destruction of laminar flow should not be used. Insensitivity to small geometric variations makes it inadvisable to attempt to design high-gain devices which depend for their performance on the critical placement of walls or wedges.

The only known element which does not depend on either walls or laminar breakdown yet has adequate gain for digital logic circuits is the reaction amplifier. Attempts to improve fluid logic elements will probably show a trend toward elements employing the principles of control jet reaction.

Low Reynolds number operation and low-gain devices make desirable the use of multistate logic elements, such as those developed under this contract. The logical design rules for use with these elements require that each multistate element be both preceded and followed by a control jet reaction element.

It might at first appear that the limited fan-in and fan-out capabilities of low-gain elements would result in much cascading of elements. Although this is true, it should be remembered that an element is nothing more than a jet interaction region, and in an integrated package these regions can be packed extremely close together. Also the multistate elements will result in some simplification of the logical design and will partially offset the need for cascading elements. A further objection to the use of low-gain elements might be that since more low-gain elements would be required for performing a specified logical function, more power would be needed by a circuit employing these elements than by a circuit employing high-gain elements. This objection is not valid because low-gain elements can be designed to function satisfactorily at much lower Reynolds numbers than high-gain elements. Indeed, it is the extremely low Reynolds number operation of the low-gain elements that opens the way to rapid advances in digital fluid logic systems.

#### SECTION 6

#### THE DESIGN PHILOSOPHY OF FLUID AMPLIFIERS

#### 6-1. THE WALL EFFECT

A two-dimensional jet of fluid directed close to a wall will tend to be drawn toward it. This phenomenon is called wall attraction and is the basic mechanism underlying the operation of the flip-flop developed by the Harry Diamond Laboratories. The reason for the use of a wall was to increase the angle through which the power jet could be deflected and thus to improve the gain.

Figure 6-la shows a power jet being acted on by a control jet. The undeflected position of the jet centerline is shown by line A, and the deflected position is shown by line B.

Figure 6-1b shows the same power jet being acted on by the combined effect of the control jet and walls 1 and 2. Wall 1 attracts the power jet to the right of the centerline when no signal is present, while wall 2 attracts the power jet to the left when the control signal is present. It is clear that the presence of walls 1 and 2 can increase the effectiveness of the control jet by amplifying the angular deflection which would have been produced by the control jet in the absence of walls.

Figure 6-2a shows the relationship between the angle of deflection of a constant power jet plotted against the control jet velocity when no walls are present, while Figure 6-2b shows the relationship between the same two variables after walls have been added. We note that a drastic change in the performance of the device results from the addition of the walls and that much greater deflections can be realized when walls are provided.

From the point of view of steady state performance it is clearly an advantage to use walls because greater control jet effectiveness can be

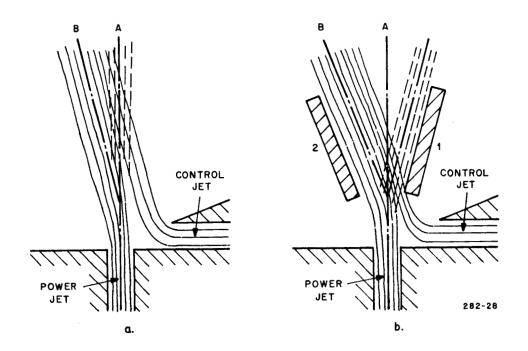


Figure 6-1. Two Methods of Deflecting a Power Jet

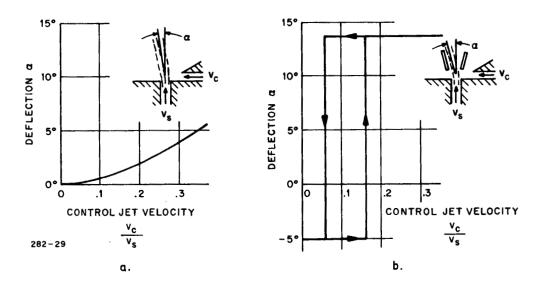


Figure 6-2. Deflections Produced by a Control Jet

achieved by this means. If we now consider the frequency response characteristics, the picture is not so clear. The hysteresis supplied by the walls produces a phase difference between an alternating input control flow and the output deflection angle  $\alpha$ . When the phase angle becomes too large the power jet is unable to follow the control jet and remains locked on one of the two walls, whereas with no walls the power jet responds to the control

jet at all practical frequencies. It appears then that the use of walls to achieve gain results in a slower element; therefore, other methods of achieving greater control signal effectiveness should be sought.

#### 6-2. THE TURBULENCE AMPLIFICATION PRINCIPLE

A laminar stream traversing an open space from a nozzle to a receiver can be broken down by means of an extremely small disturbance.

Figure 6-3a shows a laminar power stream being discharged from a nozzle 1 into undisturbed air and being picked up by receiver 2. Figure 6-3b shows how a control stream has broken down the laminar power stream into a rapidly diverging turbulent stream the energy of which has been almost totally dissipated as eddies before reaching the receiver. This device is capable of operating as an inverter with very high gain.

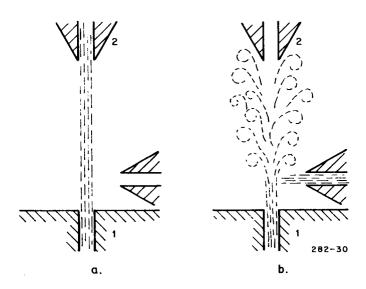


Figure 6-3. Breakdown of a Laminar Power Jet by Means of a Control Jet

If a number of control nozzles are directed toward the base of the laminar power stream we have a NOR gate with complete input and output isolation. Fan-in and fan-out capabilities of at least 4 are easily obtained, and further development of these principles shows great promise. Although their speed will be improved by miniaturization, these elements suffer from a built-in handicap. To ensure adequate dissipation of turbulent energy in the power stream when the control signal is applied, the distance between the power nozzle and the receiver, expressed in nozzle diameters, must be

much larger than that for other types of fluid amplifiers. This leads to a further difficulty: When the control jet is turned off the existing turbulent energy in the region of the receiver delays the recovery of laminar flow so that the turn-on time is almost an order of magnitude slower than the turn-off time.

### 6-3. CONTROL JET REACTION

The conventional method of introducing a control signal is to convert slow-moving air at the control signal pressure  $p_c$  to fast-moving air at the ambient pressure  $p_o$  and to allow the fast-moving control stream to impinge against the fast-moving power stream. Because momentum is conserved, the power stream is deflected through an angle  $\alpha$ , as shown in Figure 6-4a. A more effective method of introducing a control signal is to allow the static pressure  $p_c$  of the control signal to act on one side of the power jet and to permit some of the control air to accelerate along a path parallel to the power jet, as is shown in Figure 6-4b.

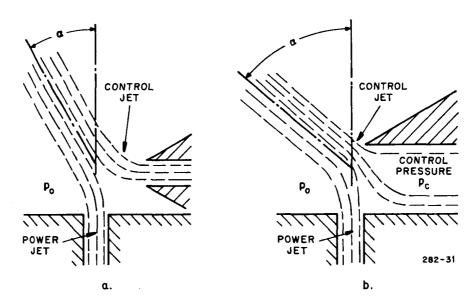


Figure 6-4. Deflecting a Power Jet by Means of a Control Jet

Based on principles to be discussed later on in this section, theoretical analyses of both types of free jet amplifiers show satisfactory agreement with experimental results. Both theory and experiment have shown that greater deflection angles a are possible by using control jet reaction rather

than by using momentum exchange. In addition to this advantage less energy is destroyed as a result of the jet interaction.

The UNIVAC inverter used the control jet reaction principle together with some wall attraction. The wall was necessary in order to obtain the fan-in and fan-out requirements, but it resulted in a speed penalty. What is needed, therefore, is a device which does not depend on wall attraction but which has adequate gain for digital logic circuits.

## 6-4. THE NEED FOR A WORKABLE THEORY

Any study whose aim is a recognizable product benefits when a set of rules and a working theory are established. Many studies, such as alchemy and astrology, were held back primarily because they appealed to authority rather than to scientific scrutiny, which demands that logic be demonstrated by means of a mathematical model.

The most dramatic advances in science have been made in areas where theory is not only advanced but usable. In some fields, such as the theory of structures, the end product shows a preference for mathematical simplicity, as typified by the suspension bridge rather than the statically indeterminate structures of a bygone age. Even in aerodynamics, complex theory has been replaced by the simplifying approximations made necessary by an aesthetic demand for the mathematically obvious.

At UNIVAC we have learned the importance of being able to calculate the performance of our fluid elements before building them.

Work on company-sponsored projects and on contracts awarded by the Harry Diamond Laboratories<sup>2</sup>, the Sandia Corporation, and NASA has shown that without analytical tools, progress in developing fast fluid logic elements is likely to be slow. The NASA contract was aimed partly at overcoming the speed limitations by use of more logically powerful fluid devices. Tests showed that multistate memory elements were even slower than conventional flip-flops and that multilevel elements were impractical. The only elements which showed real promise were those multistate logic elements which did not rely on wall attraction. Fortunately, these elements could be treated analytically by use of very basic fluid mechanics, and it was agreed that we should spend most of our time studying this type of element and the logic concepts involved.

Mathematical studies have shown that it is possible to predict the performance of a low-gain element whose speed is many times that of conventional fluid logic elements. In keeping with our belief that elements for which good mathematical models exist are in general to be preferred to those for which only a vast body of experimental data exists, UNIVAC proposes that a study of the reaction amplifier be carried out. This element has adequate gain for digital logic, and its performance under steady state and transient conditions appears completely predictable. At present it is the only element for which a mathematical theory shows promise of being both accurate and practical.

## 6-5. THE MOMENTUM EXCHANGE PRINCIPLE

Historically, the first principle used in pure fluid devices was the momentum exchange concept. Here two free jets were allowed to impinge against each other, and the resultant flow was picked up by a receiver placed at a suitable location downstream.

Figure 6-5 shows the interaction region of a momentum exchange device. We shall assume that both nozzles have equal areas. Since the jets impinge in free space the momentum before and after impingement in any given direction must be constant.

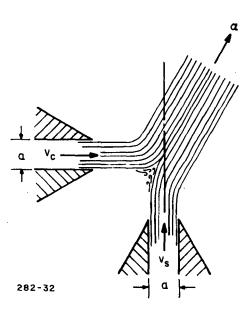


Figure 6-5. Interaction of Two Free Jets

### Consider momentum in a vertical direction:

 $\begin{array}{ll} \text{momentum of power jet} \\ \text{before impingement} \end{array} = \begin{array}{ll} \text{vertical component of momentum} \\ \text{of combined jets after impingement} \end{array}$ 

Therefore,

$$\rho \cdot Q_s \cdot v_s = \rho(Q_s + Q_c) v_v$$

$$av_s^2 = a(v_s + v_c) v_v$$

$$v_v = \frac{v_s^2}{v_s + v_c}$$
(20)

Consider momentum in a horizontal direction:

 $\begin{array}{ll} \text{momentum of control jet} \\ \text{before impingement} \end{array} = \begin{array}{ll} \text{horizontal component of momentum} \\ \text{of combined jets after impingement} \end{array}$ 

Therefore,

$$\rho \cdot Q_c v_{c_2} = \rho (Q_s + Q_c) v_h$$

$$av_c^2 = a(v_s + v_c) v_h$$

$$v_h = \frac{v_c^2}{v_s + v_c}$$
(21)

therefore, from equations (20) and (21)

$$tana = \frac{v_L}{v_c} = \frac{v_c^2}{v_s^2}$$

$$\tan\alpha = \frac{\frac{2p_c}{\rho}}{\frac{2p_s}{\rho}} = \frac{p_c}{p_s}$$

where  $p_c$  = the control total gauge pressure where  $p_s$  = the supply total gauge pressure

The loss of energy due to impingement

$$\begin{split} &= \frac{1}{2} \rho Q_{s} v_{s}^{2} + \frac{1}{2} \rho Q_{c} v_{c}^{2} - \frac{1}{2} \rho (Q_{s} + Q_{c}) (v_{v}^{2} + v_{h}^{2}) \\ &= \frac{1}{2} \rho a \left\{ v_{s}^{3} + v_{c}^{3} - (v_{s} + v_{c}) (\frac{v_{s}^{4}}{(v_{s} + v_{c})^{2}} + \frac{v_{c}^{4}}{(v_{s} + v_{c})^{2}}) \right\} \\ &= \frac{1}{2} \rho a \left\{ v_{s}^{3} + v_{c}^{3} - \frac{v_{s}^{4} + v_{c}^{4}}{v_{s} + v_{c}} \right\} \\ &= \frac{1}{2} \rho a \left\{ \frac{v_{s}^{4} + v_{s}^{3} v_{c} + v_{s} v_{c}^{3} + v_{c}^{4} - v_{s}^{4} - v_{c}^{4}}{v_{s} + v_{c}} \right\} \\ &= \frac{1}{2} \rho a \left\{ \frac{v_{s}^{4} + v_{s}^{3} v_{c} + v_{s} v_{c}^{3} + v_{c}^{4} - v_{s}^{4} - v_{c}^{4}}{v_{s} + v_{c}} \right\} \end{split}$$

The ratio:  $\frac{\text{energy lost}}{\text{energy supplied}}$ 

$$= \frac{\frac{1}{2}\rho a \left\{ \frac{v_s v_c (v_s^2 + v_c^2)}{v_s + v_c} \right\}}{\frac{1}{2}\rho a (v_s^3 + v_c^3)} = \frac{v_s v_c (v_s^2 + v_c^2)}{(v_s + v_c) (v_s^3 + v_c^3)}$$

This ratio approaches zero when either  $v_s \to 0$  or  $v_c \to 0$  and is a maximum when  $v_s = v_c$  when the ratio becomes:

$$\frac{2v_s^5}{(2v_s)(2v_s^3)} = \frac{1}{2}$$

Thus, with equal nozzle areas the ratio of lost energy to energy supplied is half when the two interacting jets have equal velocities.

# 6-6. THE CONTROL JET REACTION PRINCIPLE

We shall assume that the pressure  $p_c$  acts on the side of the supply jet (see Figure 6-6) and that the momentum imparted by the control fluid is negligible. Let the other side of the jet be exposed to atmospheric pressure;

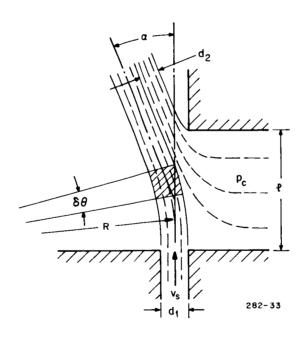


Figure 6-6. Deflection of a Power Jet Curtain

equating inertia and pressure forces acting on an element of the supply jet and assuming unit depth, we have:

Inertia force = Pressure force

therefore.

Mass × centripetal acceleration = Pressure × Area

$$(\rho d_1 R \delta \theta) \left(\frac{v_s^2}{R}\right) = (p_c)(R \delta \theta)$$

$$R = \frac{\rho d_1 v_s^2}{p_c}$$
(22)

where

R is the mean radius of curvature of the deflected supply jet

 $d_1$  is the supply jet

ρ is the fluid density

 $v_s$  is the supply jet velocity

The effective width of the control nozzle is  $d_2$ , as is shown in Figure 6-6. If this width is specified and  $p_c$  is known, the length  $\ell$  and the supply jet deflection angle  $\alpha$  may be calculated by first using equation (22) to determine the radius of curvature of the jet and then applying the rules of elementary trigonometry to specify completely the geometry of the interaction region.

A comparison between a momentum exchange amplifier and a control jet reaction amplifier was made by use of the following input specifications:

Effective power nozzle width  $= d_1$ Effective control nozzle width  $d_2 = d_1$ Power supply total pressure  $= p_s$ Control input total pressure  $p_c = 0.5p_s$ 

Calculations showed that

Deflection angle  $a_m$  using a momentum exchange device = 26.5°

Deflection angle  $\alpha_c$  using a =  $35^o$  control reaction device

The ratio  $\alpha_{\mbox{\scriptsize c}}/\alpha_{\mbox{\scriptsize m}}$  for a pressure gain of 2 is, therefore,

$$\frac{35}{26.5} = 1.32$$

Theoretically the ratio  $\alpha_c/\alpha_m$  increases rapidly as the pressure gain increases. For a pressure gain of 10 the ratio  $\alpha_c/\alpha_m$  is 3.05. This means that for higher pressure gains control jet reaction produces several times the deflection produced by momentum exchange. In addition to this advantage less energy is destroyed and, therefore, greater energy is recoverable when the control jet reaction principle is employed.

# 6-7. THE NOZZLE REACTION PRINCIPLE

A major disadvantage of the control jet reaction device is that the control port is wider than the power nozzle. This means that some diffusion must take place prior to each control input of an active element. Also, the input impedance to a control jet reaction device is not constant but depends on the extent to which the power jet has been deflected; thus, impedance matching becomes more difficult than for devices whose input impedance is constant.

The nozzle reaction device relies on the reaction of the power nozzle wall to supply a proportion of the force necessary to deflect the power jet. Figure 6-7 shows the basic layout of the jet interaction region of a nozzle reaction device. The input impedance of this device is constant because the control jet is not partially blocked by the power jet curtain, as is the case in the control jet reaction device; rather, the control jet is allowed to pass freely into the ambient atmosphere surrounding the interacting jets.

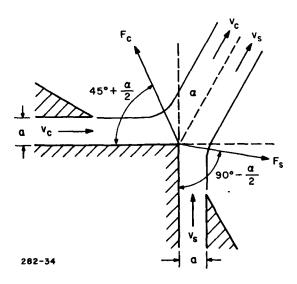


Figure 6-7. Effect of Power Nozzle Wall Reaction

We shall assume that the control jet and the power jet nozzles have the same cross-sectional area and that the jets themselves impinge without loss as shown. The resultant force  $\mathbf{F}_{\mathbf{S}}$  must make equal angles with the incident and the deflected power jet, since losses have been ignored in the interaction region. Similarly, the resultant force  $\mathbf{F}_{\mathbf{C}}$  must make equal angles with incident and the deflected control jet.

Let the deflection angle of the power jet after impingement be  $\alpha$  and let the two streams be parallel. Then the force  $F_{_{S}}$  deflects the power jet through an angle  $\alpha$  so that

$$F_{s} = (\rho \cdot Q_{s}) v_{s}^{2} \sin \frac{\alpha}{2}$$

$$F_{s} = 2\rho \cdot a \cdot v_{s}^{2} \sin \frac{\alpha}{2}$$
(23)

The force  $\mathbf{F}_{\mathbf{c}}$  deflects the control jet through an angle (90- $\alpha$ ) and thereby gives,

$$F_{c} = (\rho Q_{c}) v_{c}^{2} \sin(45 - \frac{\alpha}{2})$$

$$= \sqrt{2\rho} a v_{c}^{2} (\cos \frac{\alpha}{2} - \sin \frac{\alpha}{2})$$
(24)

At this point, the force the control jet exerts on the power jet is equal to the force the power jet exerts on the control jet. Thus, the resolved components of the forces  $\frac{F_c}{2}$  and  $\frac{F_s}{2}$  in a direction perpendicular to the resultant jet streams must be equal

$$\frac{\mathbf{F_c}}{2}\sin(45+\frac{\alpha}{2}) = \frac{\mathbf{F_s}}{2}\sin(90-\frac{\alpha}{2})$$

therefore

$$F_{c}\sqrt{2(\cos\frac{\alpha}{2} + \sin\frac{\alpha}{2})} = F_{s} \cos\frac{\alpha}{2}$$
 (25)

Substituting for  $\mathbf{F}_{\mathbf{S}}$  in equation (23) we get

$$F_c\sqrt{2(\cos\frac{\alpha}{2} + \sin\frac{\alpha}{2})} = 2\rho a v_s^2 \sin\frac{\alpha}{2} \cos\frac{\alpha}{2}$$

therefore

$$F_{c} = \frac{\sqrt{2\rho a v_{s}^{2} \sin \frac{\alpha}{2} \cos \frac{\alpha}{2}}}{\cos \frac{\alpha}{2} + \sin \frac{\alpha}{2}}$$

And substituting for  $\mathbf{F_c}$  in equation (24) we get

$$\frac{\sqrt{2\rho a v_s^2 \sin^2_2 \cos^2_2}}{\cos^2_2 + \sin^2_2} = \sqrt{2\rho a v_c^2} (\cos^2_2 - \sin^2_2)$$

therefore,

$$\frac{v_{c}^{2}}{v_{s}^{2}} = \frac{\sin \frac{\alpha}{2} \cos \frac{\alpha}{2}}{(\cos \frac{\alpha}{2} + \sin \frac{\alpha}{2})(\cos \frac{\alpha}{2} - \sin \frac{\alpha}{2})}$$
$$= \frac{\sin \alpha}{\cos \alpha}$$
$$= \tan \alpha.$$

Therefore, the ratio of the control pressure  $\boldsymbol{p}_{\boldsymbol{c}}$  to the supply pressure  $\boldsymbol{p}_{\boldsymbol{c}}$  is given by

$$\frac{\frac{2p_c}{\rho}}{\frac{2p_s}{\rho}} = \tan\alpha$$

or

$$\frac{p_c}{p_s} = \tan \alpha$$

This result is exactly the same as for the momentum exchange device; however, the design of the element is different in that the two nozzles are not isolated from each other but share a common wall which contributes to a more efficient interaction between the two jets and hence to a greater possible energy recovery at the receiver.

The advantage of a more efficient element is twofold. With higher energy recovery there is more available control energy at the next active element. This permits a redesign of the active elements by making use of the higher value of  $\frac{\dot{p}_c}{p_s}$  and hence a larger deflection angle  $\alpha$ . A large deflection angle permits placement of the receiver closer to the power nozzle with the result that even higher energy recoveries occur. Also, by minimizing the distance between the power nozzle and the receiver the molecular transport time for the fluid is reduced, and, consequently, the switching time of the element is reduced.

When momentum exchange devices are used larger power jet deflection angles result in greater energy loss ratios, but when nozzle reaction devices are used the energy loss ratios are independent of the deflection angles and depend only on viscous stresses and turbulent mixing.

## 6-8. TRANSIENT RESPONSE

The response of fluid amplifiers, which make use of either wall effects or turbulence, to a suddenly applied control signal has always been difficult to analyse theoretically because the complex aerodynamic principles on which these elements depend are not yet understood. Schlichting has studied nonsteady boundary layers and the development of turbulence and has shown that an analytical treatment which does not take into account all the terms in the general three-dimensional Navier-Stokes equations is at best only a crude approximation for high Reynolds numbers. For low values no analytical approach has yet been devised, although large scientific computers can now solve numerically a simplified two-dimensional approximation; even so, the value of this approach has not yet been demonstrated.

Tests carried out on high-gain devices have shown that switching times are invariably slower than might be expected on the basis of molecular transport times. It is certain therefore that the destruction of a boundary layer or the re-establishment of laminar flow is a time-consuming effect which is likely to prove insurmountable even when the aerodynamics are completely understood.

In contrast to the complexities introduced by high-gain elements, tests carried out on momentum exchange devices show that very elementary theory is involved in determining switching times with reasonable accuracy. As an example, let us calculate the switching time of a low-gain momentum-type or reaction-type element operating on air at a power supply pressure of 20 inches of water. Let the distance from the nozzle to the receiver be 0.050 inch. Then the switching time in response to a step input may be calculated as follows:

Switching time =  $\frac{\text{distance from nozzle to receiver}}{\text{velocity of air leaving nozzle}}$ 

Air discharging into the atmosphere under a supply pressure of 20 inches of water leaves the nozzle with a velocity of approximately 300 feet per second.

Thus,

Switching time = 
$$\frac{0.050}{12 \times 300}$$
 seconds

= 13.9 microseconds

This speed is several orders of magnitude faster than has been obtained with high-gain devices and should result in a re-evaluation of the possible applications of pure fluid logic elements.

Because control jet reaction devices do not depend on sensitive boundary or turbulence effects it is expected that switching times for these elements will be the same as those for momentum exchange devices and will show comparable agreement between theory and experiment.

#### SECTION 7

## DEVELOPMENT OF A FLUID ELEMENT

## 7-1. OPTIMIZATION OF FLUID ELEMENTS

Several approaches to the optimization of fluid elements have been attempted. The most successful of these approaches are described in this section.

## 1. The Adjustable Large Model

This method is suitable only as a starting point for more refined methods or for preparing elements which are intended for operation at high Reynolds numbers. It consists in making a large model by use of plastic or wood and arranging the walls so that they can be moved independently of each other. Flow visualization can be achieved by means of injecting smoke or kerosene vapor into the power or control stream.

By testing various configurations it is possible to determine which walls have a controlling influence on the characteristics. After about ten experiments of this kind, a workable design can usually be made, provided transient response is not included in the specifications. The three-state memory element was built by use of this method.

# 2. The Actual-Size Adjustable Model

This method is ideal when the general configuration has been obtained with a large model or when some preliminary investigations have indicated an approximate design. It has an advantage in that the optimized model may be used as a master from which rubber molds can be cast. Thus, it is possible to have actual working elements a few days after an optimum model has been built. The dual-output amplifier was built by use of an actual-size adjustable model in which the separate pieces were merely stuck together with double-sided masking tape and moved until the desired characteristics were obtained.

Figure 7-1 is a photograph of the four steps, or stages, in the construction of a plastic element. Figure 7-1a shows a full-size adjustable element, Figure 7-1b shows a rubber mold of the element, Figure 7-1c shows a plastic casting of the element, and Figure 7-1d shows a finished element. Figure 7-2 is a photograph of a 3-5 element made from an actual-size adjustable model.

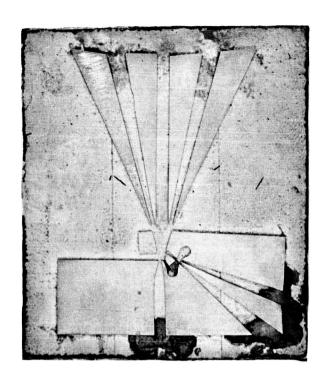
# 3. "Shaving and Building"

A plastic casting may not possess quite the desired characteristics when tested prior to bonding on its cover. Its performance may sometimes be improved by carefully shaving some of its critical walls or by building them up with modelling clay. A rubber mold may then be made of the "touched-up" element, which then becomes a new master. The disadvantage of this method is that the end product frequently would be found to have many irregularities with the result that a detailed drawing of such an element would be almost impossible. Figures 7-3 and 7-4 are photographs of a tristable memory element and a dual-output amplifier, respectively, which were built by means of the shaving and building method.

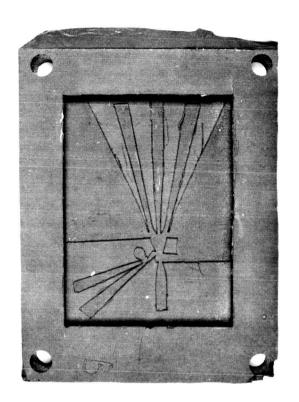
# 4. Drawing Board Design

Low-gain elements lend themselves to a theoretical treatment, and it has been found possible to design elements by use of the theory discussed in Section 6 and to compensate for departures from theory by assuming loss coefficients in determining the pressure recovery. This approach uses the basic geometry established by the calculations. An element is built exactly in the form in which it is shown in the drawing by preparing a template and using a pantograph milling machine to cut an actual-size model in brass or plastic. The model is tested, and the results are compared with those predicted. The calculations are repeated by use of the new experimental data, and a new design is prepared. After about three attempts it will be found that the calculated and the actual performance of an element will agree satisfactorily, provided that no dependence has been placed on wall attraction phenomena.

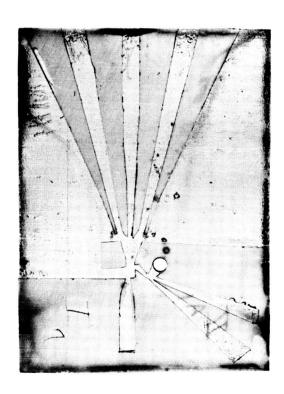
In principal this method is valid for all types of pure fluid elements. It is, however, more time-consuming than the others when extremely high gain is sought. Figures 7-5 and 7-6 show a 2-3 element and a low-gain amplifier, respectively, built by use of this method.



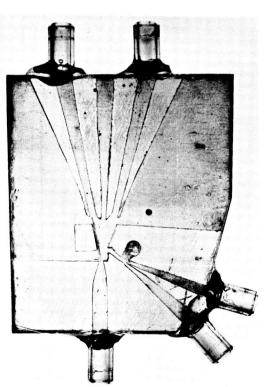
a. Adjustable Model



b. Rubber Mold



c. Plastic Casting



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d. Finished Element

Figure 7-1. Stages in the Construction of a Plastic Element

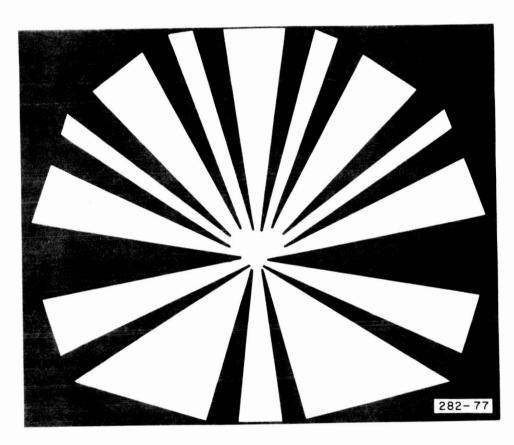


Figure 7-2. 3-5 Element

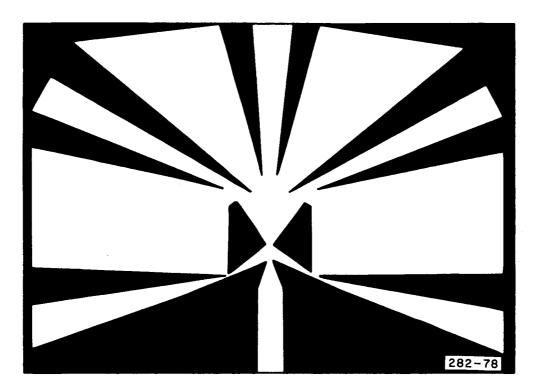


Figure 7-3. Tristable Memory Element

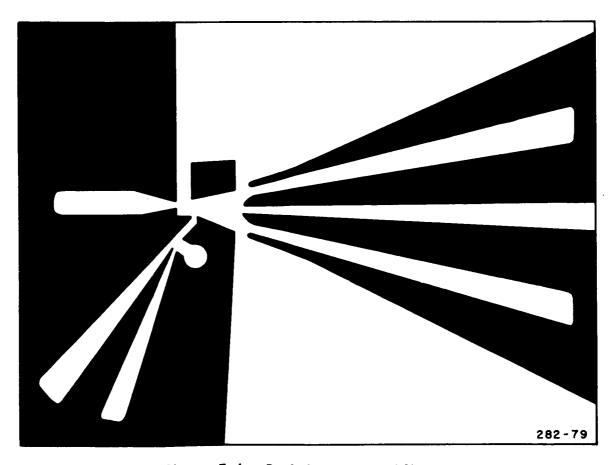


Figure 7-4. Dual-Output Amplifier

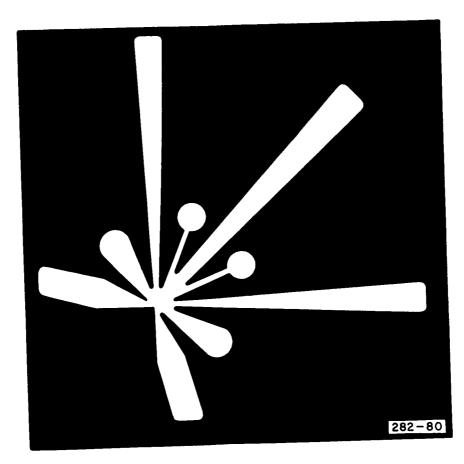


Figure 7-5. Three-Output 2-3 Element

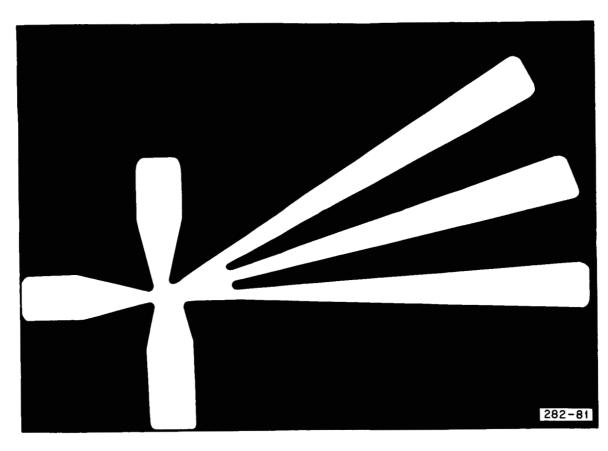


Figure 7-6. Low Gain 2-2 Element

#### SECTION 8

## EXPERIMENTAL RESULTS

# 8-1. STEADY STATE CHARACTERISTICS

The final characteristics of all multistate elements which could be fabricated reliably are shown graphically. Figure 8-1 shows that a very low signal at input B is required for switching the flow from output leg  $\mathbf{A}_{\mathbf{O}}$ 

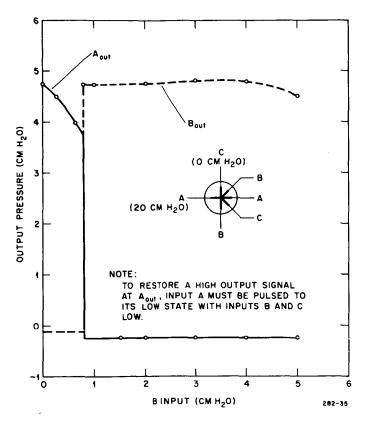


Figure 8-1. Steady State Characteristics of a Three-Output Memory Element

to output leg  $\mathbf{B}_{\mathbf{0}}$ . Since the element is symmetrical the switching signals at B and C are equal. An important characteristics of this element is that

output  $\mathbf{A}_{\mathbf{0}}$  can be restored to its high state only if the inputs are all low prior to the application of signal  $\mathbf{A}$ .

Figure 8-2 shows the variation in two output signals when input A is held constant and input B is varied from zero to the value of signal A. Clearly, although the element is analog in its mode of operation, the specified logical functions are obtained when binary inputs are applied.

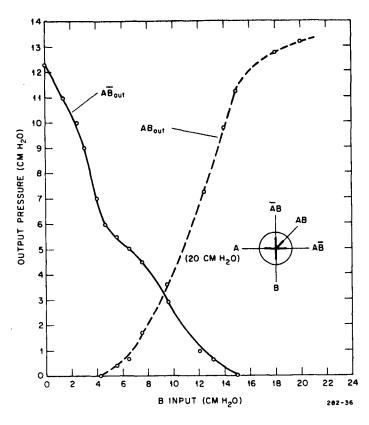


Figure 8-2. Steady State Characteristics of a 2-3 Element

Figure 8-3 shows characteristics similar to those shown in Figure 8-2. However, the pressure losses are greater because it was necessary to place the receivers farther away from the nozzles than for the 2-3 element. Again, the element is analog in its mode of operation and needs to be used in conjunction with an amplifier with a well-defined OFF or ON state.

Figure 8-4 shows the characteristics of a dual-output amplifier with well-defined OFF and ON conditions and a narrow analog region. Inputs A and B were found to produce identical characteristics.

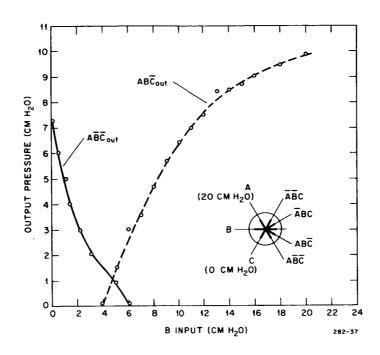


Figure 8-3. Steady State Characteristics of a 3-5 Element

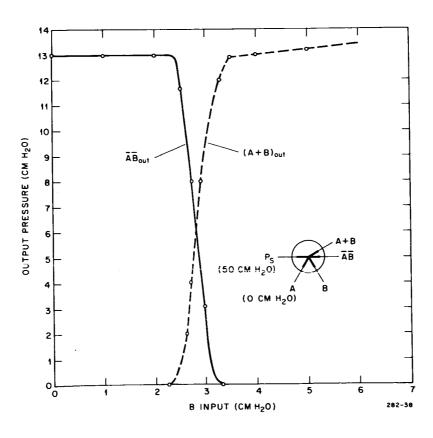


Figure 8-4. Steady State Characteristics of a Dual-Output (High-Gain) Amplifier

Figure 8-5 shows the characteristics of a passive element designed to produce sufficient gain to permit cascading. The gain is achieved by introducing at A a signal derived from an active element and at B a signal derived from a passive element. In this way one passive element can drive another in a chain indefinitely. The only criterion is that each A input must be driven by an active element.

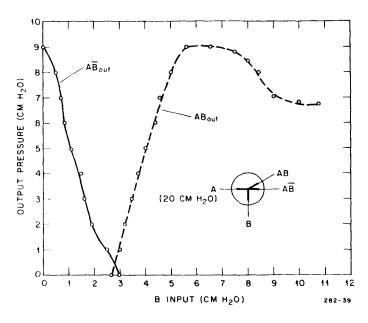


Figure 8-5. Steady State Characteristics of a 2-2 (Low-Gain) Element

## 8-2. TRANSIENT RESPONSE

Experiments carried out on the queueing register using the three-state memory element showed that the maximum rate of word transport was only 37 bits per second. The three-state element was extremely slow to switch, and it seemed that wall attraction was responsible.

To verify this assumption a pure fluid oscillator was built by use of the 2-2 (low-gain) element. This element was designed by use of the theory described in Section 6. It does not depend for its gain on wall attraction.

Figure 8-6 shows the cycle time plotted against the length L of the feedback path. The curve is extrapolated to the L=0 ordinate, and the cycle time is seen to be approximately 0.4 millisecond; consequently, the switching time is 0.2 millisecond. Calculations have shown that this switching time depends only on the molecular transport time of the fluid in passing from the nozzle to the receiver. In general, any fluid circuit contains

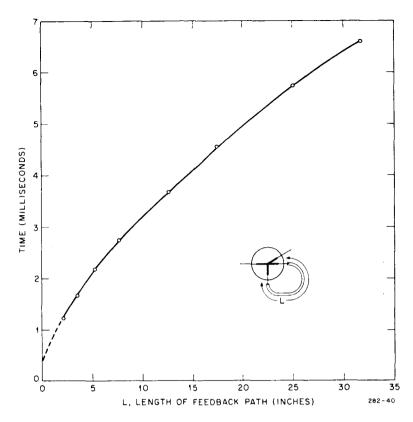


Figure 8-6. Transient State Characteristics Giving Cycle Time of a Low-Gain Oscillator

inductance in its interconnecting lines. This inductance will affect the input rise time and hence the switching time of subsequent elements.

Transient response tests on complex circuits were outside the scope of these investigations but will certainly need to be carried out before truly reliable estimates can be made of system speed.

#### SECTION 9

#### CONCLUSIONS AND RECOMMENDATIONS

Multistate elements may be classed as follows:

- 1. Multilevel with memory
- 2. Multilevel without memory
- 3. Multioutput with memory
- 4. Multioutput without memory

Tests have shown that the only satisfactory elements which could be built were in classes 3 and 4. The class 3 element found at least one useful application, the asynchronous shift register, but was relatively slow; whereas the class 4 element has been shown to be a powerful logic element with a capacity for high speed and an insensitivity to small geometric variations not found in any other class of element. Tests carried out on class 4 elements suggest that operation at very low Reynolds numbers should be possible although insufficient quantitative data have been obtained to show what the lower limit might be.

It appears from these conclusions that future investigations should involve class 4 elements used in conjunction with amplifiers of moderate gain. Tests should be carried out on complex circuits to determine system reliability and speed. A parallel effort should be made to determine the scope of recent concepts in bionics in which it appears that limitations of speed may be overcome by asynchronous polymorphic logic in much the same manner that the brain apparently overcomes these limitations. Majority logic and variable threshold logic elements may be synthesized from the basic fluid elements developed under this contract, and it is now conceivable that miniature fluid elements may be integrated to form thousands of interconnected "neurons" to perform that quasidigital type of logic now associated with the

brain. If this should prove feasible we would be one step closer to the adaptive machine having high-order artificial intelligence.

#### APPENDIX A

#### THE NASA FLUID MATHEMATIC UNIT

## A-1. GENERAL DESCRIPTION

The unit illustrated in Figure A-1 consists of a four-bit binary adder with associated registers and a console. All operations are under manual control from the console.

A storage register S stores the number to be added to the accumulator AC. When the add signal is generated from the console, the sum of the contents of AC and S is stored in the intermediate storage register A. After the add signal is removed, the contents of A are transferred to AC. The AC and S registers are displayed in console indicators. A clear signal can be generated from the console to set the accumulator to binary O.

## A-2. S REGISTER

The S register contains four flip-flops each of which can be set and reset from the console. The outputs of the S register feed the binary adder.

# A-3. THE ACCUMULATOR

The accumulator consists of 2 four-bit registers. The input register A receives the sum during an add. The output register AC feeds the binary adder and is not changed during add time. Normally, the outputs of the A register control the AC register through a 3-5 element for each bit position. During add time, this path is blocked, and the new sum is set up into the A register. After the add signal from the console is removed, the new sum is gated to the AC register.

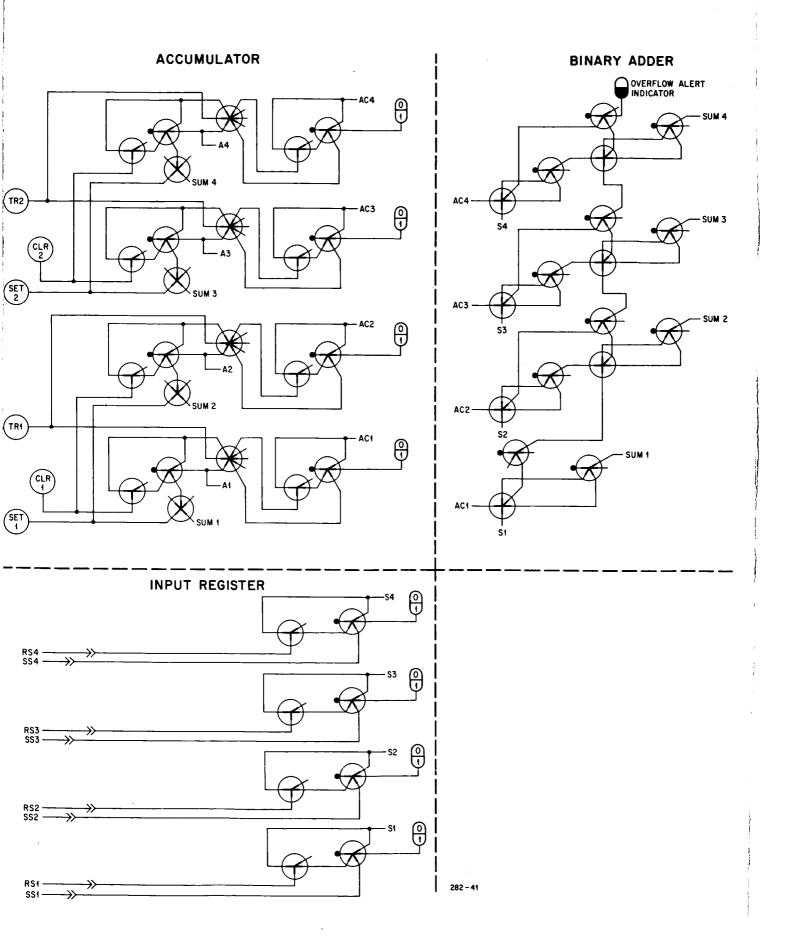
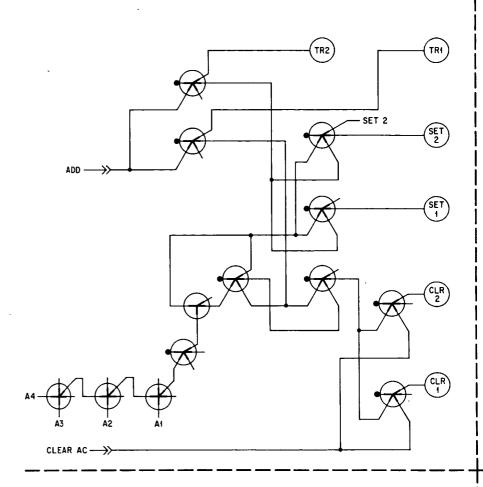
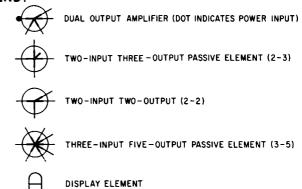


Figure A-1. Four-Bit Binary Adder

## CONTROL



# LEGEND:



SIGNAL FROM CONSOLE

## A-4. BINARY ADDER

The binary adder is a combinational net composed of dual-output inverters and 2-3 elements. The inputs are from the S and AC registers. Each stage generates a sum and a carry which is an input to the succeeding stage. The carry from the fourth stage is used to drive an "overflow alarm" indicator on the console. If the operands currently in the AC and S registers will cause a carry from the fourth bit position when added, overflow alarm will be indicated on the console.

## A-5. CONTROL

The control logic generates and times the signals necessary to do the add. The initiating signal, ADD, comes from the console on command of the operator. Three other signals are generated when the ADD signal is received by the control logic.

- 1. TR: isolates the AC register from the A register by way of the elements coupling the registers.
- 2. CLR: clears the A register to binary O.
- 3. SET: gates the sum into the A register.

Relative timing is shown in Figure A-2.

A photograph of the fluid arithmetic unit is shown in Figure A-3.

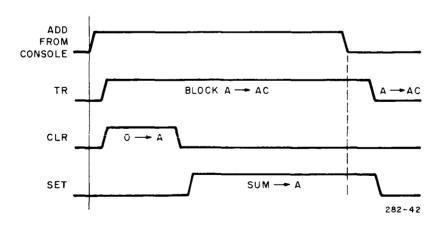


Figure A-2. Relative Timing



Figure A-3. Fluid Arithmetic Unit

## APPENDIX B

#### DEVELOPMENT OF DUAL-OUTPUT INVERTER

## B-1. GENERAL

After a discussion with both M. Jacoby and T. D. Reader, it was decided to begin with testing a design (DOI No. 1) by T. D. Reader, to determine the performance characteristics.

A template has been made, and an 0.026-inch-size device has been machined from this template. Figure B-1 shows all the dimensions of the template.

Two tests have been conducted to determine the performance characteristics of the 0.026-inch-size device—to be referred to as DOI No. 1 (Dualoutput Inverter Design No. 1) in the following report.

<u>First Test</u>: To check the stability of DOI No. 1 with respect to the jet supply pressure. The power jet supply pressure was varied from 0 to 38 inch water gauge and both the state and the recovered stagnation pressure of the power jet were observed. The test arrangement is shown in Figure B-2.

The test result indicates that the stability of DOI No. 1 depends on the power jet supply pressure,  $P_s$ . At several values of  $P_s$ , the power jet became unstable and switched automatically to the not preferred (normally OFF) side of the output channels. This is due to the fact that the reattachment wall of the control port side is in the power jet flow and splitting part of the power jet into control port, and thus builds up enough pressure to switch the power jet to the normally OFF output. It is necessary, therefore, to provide isolation at the control input. Second test to be reported below was made with isolator at the control input.

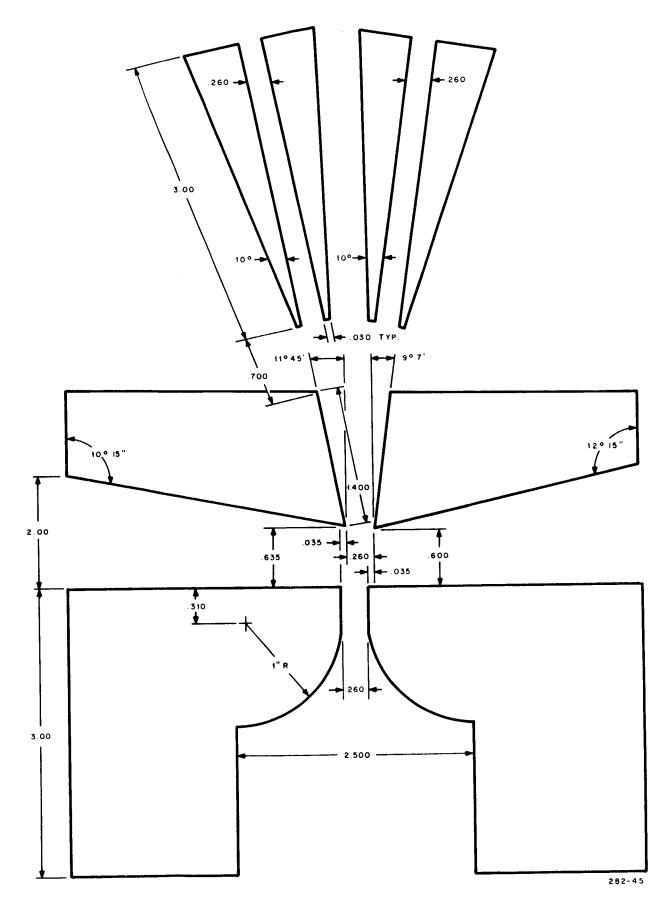


Figure B-1. Template for DOI No. 1 Design

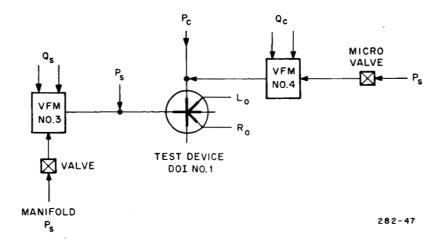


Figure B-2. Test Arrangement (Without Isolator)

<u>Second Test</u>: The objective here is to determine the possible gain of DOI No. 1 with isolated control input.

The test arrangement is shown in Figure B-3.

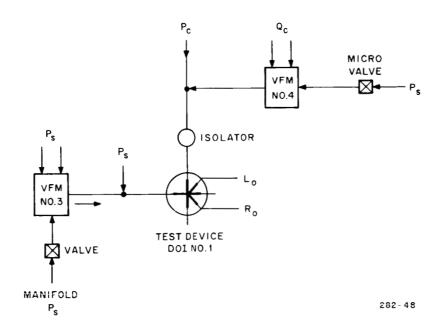


Figure B-3. Test Arrangement (With Isolator)

Figure B-4 was plotted from the test data and shows:

(1) The ratio of the normally ON output  $P_{ol}$  to the control input  $P_c$  required to switch the power jet to normally OFF output with respect to  $P_s$ . The power jet supply pressure  $P_s$  was varied from 0 to 38 inch water gauge. It was noticed that at a range of  $P_s$ , there is a considerable amount of noise.

The maximum possible gain as indicated by  $P_{\mbox{ol}}/P_{\mbox{c}}$  curve is about 5.

(2) The ratio of the normally OFF output  $P_{or}$  to the control input  $P_c$ . The ratio  $P_{or}/P_c$  can be interpreted as the gain of the inverter when used as an amplifier. This gain is different (lower) from the previous gain described in (1). There is also a range of  $P_s$  in which noise exists.

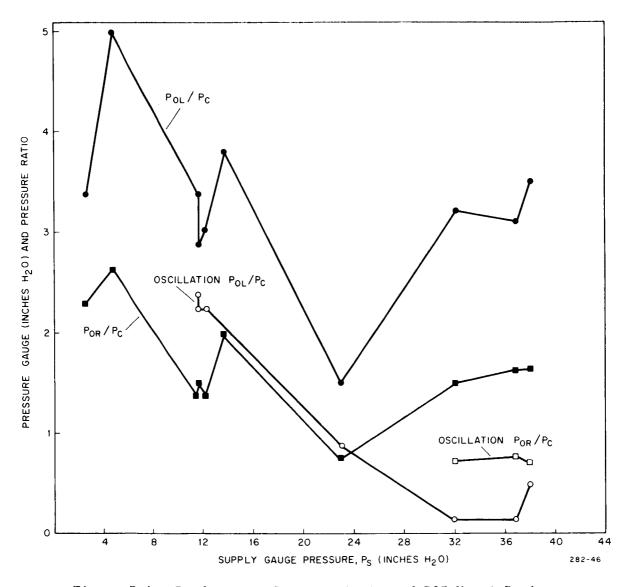


Figure B-4. Performance Characteristics of DOI No. 1 Design

## B-2. CONCLUSION

The performance characteristics of DOI No. 1 have been determined and presented. Although the fan-in and fan-out parts of the device were not built in and tested, the performance characteristics of a complete device (with fan-in and fan-out of 4 each incorporated in the present design) should not

differ appreciably from the present characteristics—maximum pressure gain of 5, some inevitable noise, and slight asymmetrical outputs. In the author's opinion, these characteristics can be improved. A continuous effort along this direction is therefore recommended.

## APPENDIX C

#### DUAL-OUTPUT INVERTER

## C-1. INTRODUCTION

This report describes the results of the effort to develop a dual-output inverter. Following the terminology used in Appendix B, the design of the dual-output inverter to be discussed here is referred to as DOI No. 2 (Dual-output Inverter Design No. 2).

## C-2. DESIGN CONCEPT

There are several basic differences in the design of the DOI No. 1 and DOI No. 2. These are:  $\frac{1}{2}$ 

- (1) DOI No. 2 is essentially symmetrical with respect to the axis of the power jet. The mono-stability was introduced after the bistability of the design was experimentally confirmed. The exact steps taken in the design of DOI No. 2 are given in a separate section of this report.
- (2) The offset of the left side wall of DOI No. 1 is negative (-0.135 times the nozzle width), whereas in DOI No. 2 it is changed to positive (+0.25 times the nozzle width).
- (3) In the design of DOI No. 2 both outputs have been fanned into four, to give eight outputs altogether. The control port is a four-input OR gate. In the design of DOI No. 1 there is no fan-in nor fan-out. This difference should be kept in mind when comparing the performance characteristics of both designs.

The specific steps taken in designing DOI No. 2 are as follows:

Step 1. It is highly desirable that all the eight outputs are equal to one another, although a small difference can be tolerated. In order to achieve this objective a perfectly symmetrical design was drawn. The design consists of four types of elements namely, flip-flop, OR gate, divider, and isolator. The designs of all the four types of elements

are chosen from those previously tested at UNIVAC. Some performance characteristics of each element were available, and they are cited in Table 1.

In this step the work was simply to combine these four types of elements properly into an integral device. The device in this preliminary design should work as a flip-flop with fan-in and fan-out of four and with performance characteristics comparable to those indicated in Table 1.

Step 2. Several test flip-flops of 0.020-inch nozzle size were made by using the pantograph. The design was drawn to the scale 20 to 1 and then reduced to 10 to 1 photographically. DYCRIL process was used to obtain the template. The template used was ten times larger than the device size.

The key to a success in the design depends totally on the performance characteristics of the flip-flop portion in the design. Although this flip-flop design was obtained by means of a large scale test model (20 times larger than device size and aspect ratio of 3 to 1) and was not tested at all in smaller sizes, past experience on scaling effect seems to warrant a try to obtain 0.020-inch-nozzle-size device.

The test result from the 0.020-inch-nozzle-size flip-flops with aspect ratio of 1 to 1, 1.6 to 1, and 2 to 1 indicated that with an aspect ratio of 2 to 1 the flip-flop begins to be bistable at an input pressure of about 22 inches water gauge or at corresponding Reynolds number of 3000 based on the velocity and width at the power nozzle. With smaller aspect ratio than 1.6 to 1, the flip-flop was not bistable.

Step 3. A complete device was made after the completion of step 2. The aspect ratio was raised to 2 to 1. There are several ways by which the device can be made to be mono-stable. For examples: the side walls can be made slightly longer on one side than the other; the angles of the side walls with respect to the power jet axis may be varied; or the control ports can be made asymmetrical. The load to the flip-flop as is represented by the output channel size and configuration can also be one of many other ways; however, there is definite difference in their resulting effect with regard to the requirement of uniform

Table C-1. Test Data-Design H, 0.400 Inch Model. Aspect Ratio 3:1 (Depth to Nozzle Width)

Conditions	V power jet [fps]	(2) Voutput [fps]	(3) Voffside [fps]	V control [fps]	(5) Pressure Gain [Column (2)] [Column (4)]	(6) Flow Gain $\sqrt{\text{column }(5)} \times \frac{\text{A_out}}{\text{A_in}}$	(7) Load Sensitivity
1. Load 3D (Driving 3 similar devices) 2. Test Reynolds Number = 1.12 × Rmin = 1.12 × 2000 = 2250 (i.e., △0 <sub>DFM</sub> 0.3125 = 2.0 in WG)	$\begin{pmatrix} X = 0 \\ (Y = -0.4) \end{pmatrix}$ E = 7.4  volts V = 8.8  fps	(X = +1.4) (Y = 12.3) E = 6.7  volts V = 2.0  fps	V ‡ O fps See Load Sensi- tivity	(X = -3.1) (Y = -1.6) E = 6.0  volts V = 0.2 - 0.4  fps	$\left(\frac{2.0}{0.2}\right)^2 = 100$	30	Blocked: Divided, Bistable 1D: Divided, Bistable 1.50: Slight Entrainment, Bistable >20: Entrainment, Bistable
1. Load 3D (Driving 3 similar devices) 2. Test Reynolds Number = 1.5 × Rmin = 1.5 × 2000 = 3000 (3h <sub>0</sub> P <sub>M</sub> 0.3125 = 3.7 in WG)	E = 7.7 volts V = 12.8 fps	E = 7.0 volts V = 4.3 fps		E = 6.05 voits V = 0.2-0.4 fps	$\left(\frac{4.3}{0.2}\right)^2 = 462$ or $\left(\frac{4.3}{0.4}\right)^2 = 108$	64.5	Same as above.

Conclusions:

(1) Pressure Gain 25-100 108-462

Flow Gain 15-30 32.2-64.5

(2) Load Sensitivity—as shown above

outputs. In DOI No. 2, the method of biasing the flip-flop was the one of lengthening the side wall. It was expected to cause negligible effect as far as the outputs uniformity is concerned.

A simple steady state test of the complete device would indicate usually that there is a slightly preferred side even before the flip-flop is biased. After the slightly preferred side of the flip-flop is found, it is a rather simple task to increase this tendency to any degree as desired. The stronger the flip-flop is biased the harder it becomes to switch, and therefore, it results in a low gain device. The gain can also be changed by altering the OR gate design and its relative location with respect to the flip-flop.

<u>Step 4.</u> The uniformity of the outputs and the degree of isolation were checked in this step. Also, minor changes in the design such as arranging the inputs and outputs in a manner convenient for interconnection of devices can be made in this step.

# C-3. PERFORMANCE CHARACTERISTICS OF DOI No. 2

Figure C-1 shows the test arrangement used to obtain performance characteristics of DOI No. 2. A test device of DOI No. 2 as shown in Figure C-2 has been milled on a Plexiglas plate. Some performance characteristics have been obtained and presented in Figures C-3, C-4, C-5, C-6, and C-7.

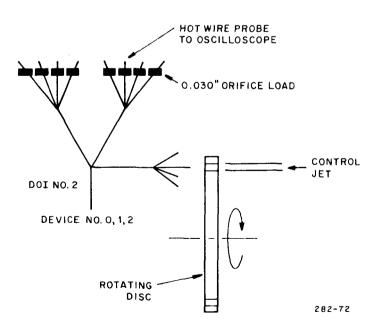


Figure C-1. Test Arrangement

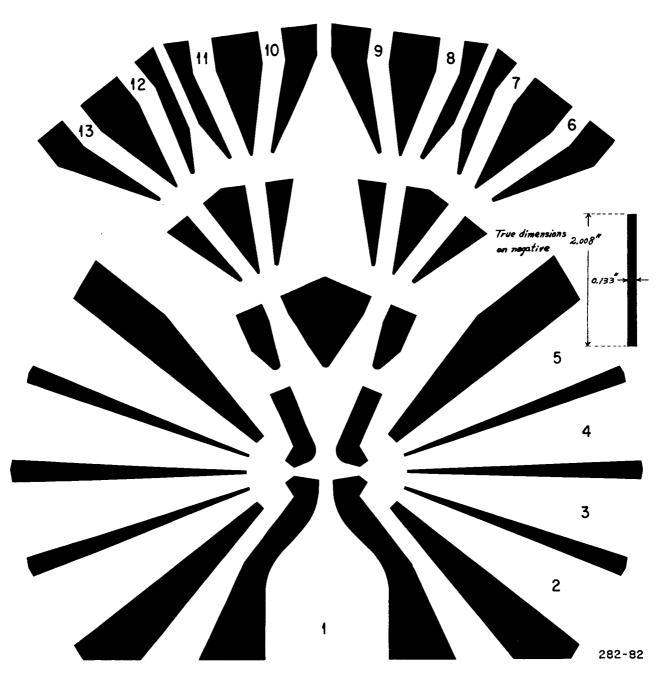


Figure C-2. DOI No. 2 Design

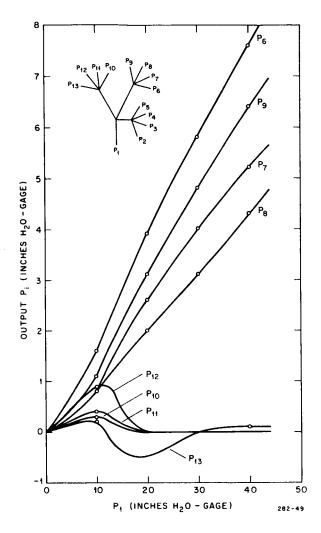


Figure C-3. Device No. O Static Characteristics (Output Blocked)

Two epoxy cast copies of the device made through the rubber mold process have also been tested. These results are presented in Figures C-8 through C-18. The main concern in testing the copy devices was to find out whether the device can be reproduced by using epoxy and rubber mold casting process. The reproduction was found not to be faithful as we have experienced previously. The power nozzle width of the master and the two copies were found to be 0.021 inch, 0.023 inch, and 0.023 inch, respectively. This is equivalent to a deviation of approximately 10 percent in one of the key dimensions in the design. For the convenience in the following presentation, the test device milled on a Plexiglas plate is to be called Device No. 0, and the two copies, Devices No. 1 and No. 2.

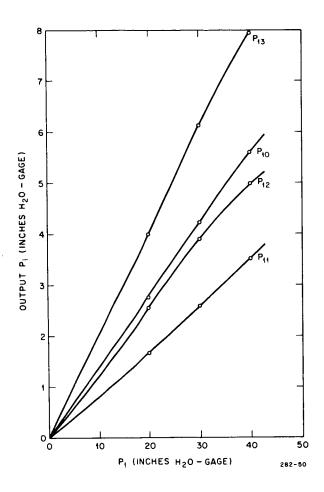


Figure C-4. Device No. O Static Characteristics (Output Blocked)

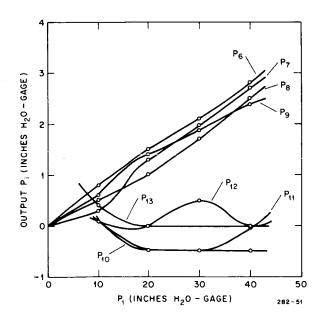


Figure C-5. Device No. 0 Static Characteristics (Loaded With 0.030 Orifice)

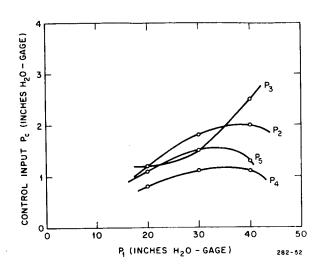


Figure C-6. Device No. O Switching Test (Output Blocked)

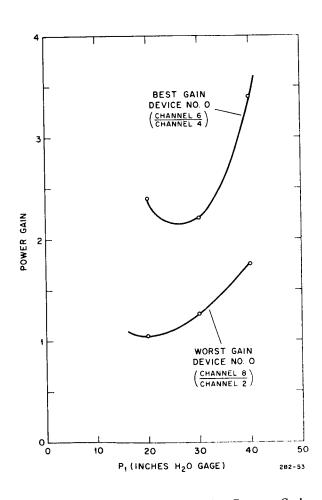


Figure C-7. Variations in Power Gain

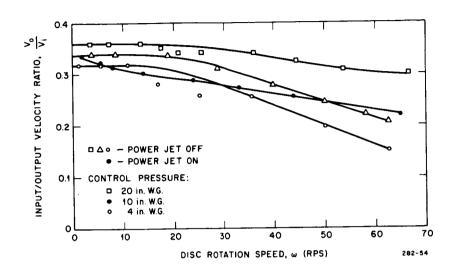


Figure C-8. Impedance of the Control Channel Versus Frequency of Operation

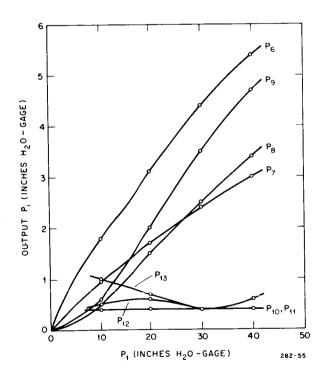


Figure C-9. Device No. 1 Static Characteristics (Output Blocked)

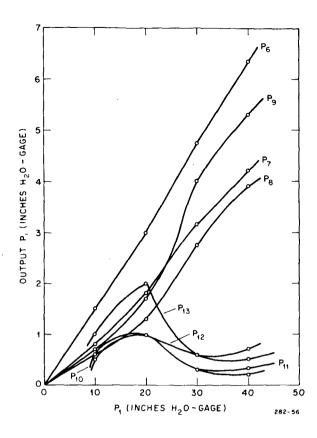


Figure C-10. Device No. 2 Static Characteristics (Output Blocked)

Some of our objectives concerned in this design are the output uniformity and the lowest power level of operation. Figures C-3, C-4, and C-5 show these aspects of Device No. 0. The uniformity of the normally ON outputs is indicated by the degree of dispersion among the curves  $P_6$ ,  $P_7$ ,  $P_8$ , and  $P_9$  in Figure C-3 and  $P_{10}$ ,  $P_{11}$ ,  $P_{12}$ , and  $P_{13}$  in Figure C-4. The ratio of the highest and lowest output is about 2 when the output ports were entirely blocked; whereas when the outputs were loaded with 4 0.030-inch orifices, which simulate the condition of driving 4 similar devices, the uniformity is rather good, as can be seen from Figure C-5. The lowest power level of operation can be estimated from Figures C-3 and C-5. The device is not mono-stable at  $P_1$  below 10 inches water gauge since both sets of curves consisted of  $P_6$ ,  $P_7$ ,  $P_8$ ,  $P_9$ , and of  $P_{10}$ ,  $P_{11}$ ,  $P_{12}$ , and  $P_{13}$  are practically indistinctive. At values of  $P_1$  above 20 inches water gauge the device is definitely mono-stable. Therefore, the lowest power level of operation lies between 10 to 20 inches water gauge, probably closer to 10 inches water gauge.

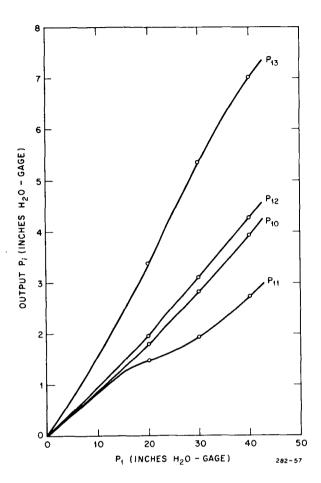


Figure C-11. Device No. 1 Static Characteristics (Output Blocked)

The corresponding Reynolds number of 10 inches water gauge is 2230. Figures C-3 and C-5 also show the steady state noise level. In the operational range of the device, the maximum noise level is 0.5 inch water gauge, when the outputs are loaded with 0.030-inch orifices; whereas when the outputs are blocked the noise level is much lower.

Figure C-6 shows the result of a quasi steady state switching test. The switching pressure requirement of the four control inputs are not perfectly uniform, more diversed at higher  $P_1$  value than at lower. When the switching pressure and flow are considered in the form of switching power requirement (PQ); and the output power is calculated from the output pressure and flow when loaded with 0.030-inch orifice, then the ratio of the latter to the former is taken as the power gain, for example,

 $Power \ gain = \frac{Output \ power \ (static \ pressure \ at \ the \ orifice - flow \ through \ orifice)}{Control \ input \ (static \ pressure - flow \ at \ control \ port)}$ 

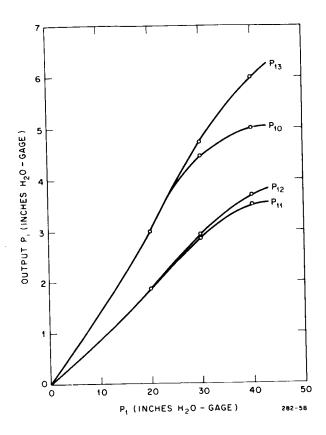


Figure C-12. Device No. 2 Static Characteristics (Output Blocked)

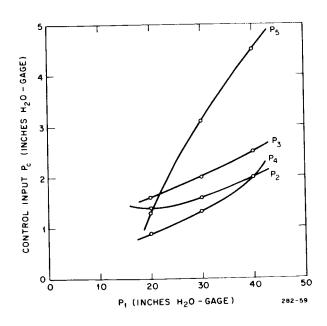


Figure C-13. Device No. 1 Switching Test (Output Blocked)

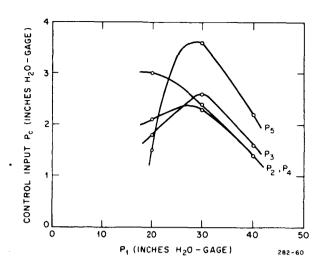


Figure C-14. Device No. 2 Switching Test (Output Blocked)

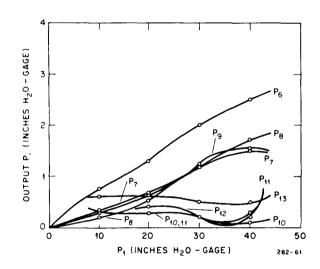


Figure C-15. Device No. 1 Static Characteristics (Loaded With 0.030 Orifices)

Figure C-7 shows the best and worst power gain in the operational range of the device. The curves showing the best power gain are calculated from the data on the highest output (No. 6 output) and the lowest switching requirement (No. 4 control input). Similarly, the worst power gain is obtained from the data on the lowest output power (No. 8 output) and the highest switching requirement (No. 2 control input). Figure C-7 indicates the values of gain ranges from 1 to slightly over 3 depending on the power jet pressure level  $P_1$ . Throughout the range, the best gain values are approximately twice the values of the worst gain. When the device is to be operated at a higher frequency, say at kilocycle level, it is foreseen that a

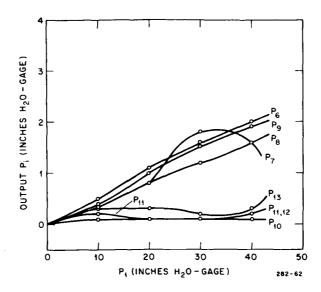


Figure C-16. Device No. 2 Static Characteristics (Loaded With 0.030 Orifices)

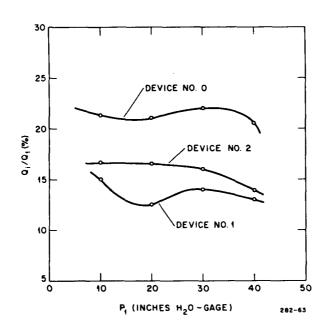


Figure C-17. Flow Recovery

somewhat higher gain design then that of DOI No. 2 would be required. Also, at the kilocycle frequency, the interconnection by means of TYGON tubing as currently in use is unsatisfactory. However, before eliminating it completely, the interconnection by TYGON tubing of sizes compatible to device channel size could still be used between module blocks.

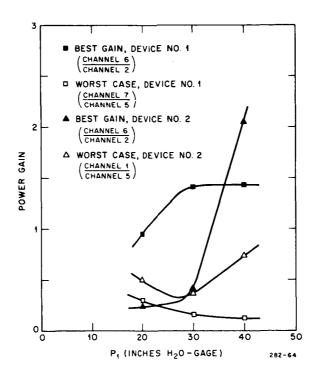


Figure C-18. Variations in Power Gain

# C-4. DYNAMIC PERFORMANCE

The main concern at the present state of development, with regard to the DOI No. 2 design, is to find out how fast can we drive the device if a sufficient switching pulse were applied at the control ports. From previous experience (switching test performed in HDL contract for Pure Fluid Binary Counter Design), it is known that the effectiveness of the control pulse drops considerably as the device is operated at progressively higher frequency. Figure C-8 shows a test result from the HDL contract work mentioned above. It can be reduced from this figure that driving the HDL flip-flop at a frequency of 120 pulses per second, the effectiveness of the pulse is 50 percent of the steady state test value; and that the effectiveness (as expressed in terms of the percentage of the applied control signal) is increased by raising the amplitude of the control signal. From the same Figure C-8, it is seen that the effectiveness was raised to 83 percent, when the control pulse amplitude was raised from 4 inches water gauge to 20 inches water gauge.

Dynamically, the test device of DOI No. 2 design was investigated in the following manner, and some results have been obtained.

The test devices No. 0, 1, and 2 were driven by a pulse train of sufficient amplitude generated from a mechanical pulse generator, which consists of a slotted rotating disc and a jet. In the test, each device was loaded with 0.030-inch orifices. A hot wire probe was placed at the output to see if the device was switching clearly as the driving signal frequency was increased. While increasing the driving pulse frequency, the amplitude of the pulse was adjusted to obtain clean switching.

In this manner, the device was driven satisfactorily at 50 pulses per second. From 50 up to 200 pulses per second the output from the device became more and more degraded with respect to its amplitude and noise level. Above 200 pulses per second, the device was not switching clearly.

In Figures C-9 to C-18, the corresponding test data on the Devices No. 1 and 2 are presented. By comparing each corresponding figure of Devices No. 0, 1, and 2, it is evident that the performance characteristics of the Devices No. 1 and 2 are considerably different from their master Device No. 0. This is caused mainly by the dimensional deviation when making the cast copies. For an example, it was found as mentioned previously, that the nozzle width in Device No. 0 (master) was 0.021 inch, whereas Devices No. 1 and 2 (the copies) were 0.023 inch. In terms of the original dimension, this corresponds to about 10 percent deviation. From this experience, it is obvious that when designing a fluid amplifier in mass production, the inherent deviation in the particular manufacturing process used must be taken into consideration.

# C-5. SUGGESTIONS FOR FURTHER DEVELOPMENT

- 1. The lowest power level of operation of the present design is slightly higher than 10 inches water gauge, or 2230 in terms of Reynolds number. It is felt that this value can be lowered by a minor modification in the design. From power supply point of view, this improvement is a must.
- The design must be improved to provide a somewhat higher gain than what has been achieved at present. In the author's opinion, this can be achieved rather easily by modifying the design of the input ports.
- 3. The approach taken in designing the DOI No. 2 has proved to be very promising, though minor modifications are necessary. It is suggested that in the next design the inputs and outputs arrangements be made to facilitate the assembly of the devices into systems.

#### APPENDIX D

### EVALUATION OF DYCRIL PROCESS FOR MAKING TEMPLATE

### D-1. INTRODUCTION

The DYCRIL Process has been applied to fabricate fluid devices for some time. The process and its limitations are described in detail in the report entitled, "Fluid Amplfier State of the Art" by the General Electric Company. UNIVAC's experience with the DYCRIL process has been unsatisfactory. This is based on Mr. E. R. Phillip's report when he attempted to fabricate a flipflop with the smallest cross section of 0.020 inch wide by 0.040 inch deep in the design. The process at its present state, primarily developed by the printing industry, is not applicable to fabricate fluid devices which have cross sections equal to or smaller than mentioned above.

In order to evaluate the possibility of using DYCRIL process to make the template which can be used in the pantograph to produce the desired small size fluid device, the following test on the dimensional tolerance of the process has been carried out. It is hoped that a basis for determining the desirability of establishing such a process in our Special Devices Department will be founded as a result of this investigation. The other factors which should be considered in making such a determination are summarized in the table on page 8-8 of the above-mentioned report by the General Electric Company.

# D-2. DIMENSIONAL TOLERANCE OF DYCRIL PROCESS

### A. General Description of the Test

A negative as shown in Figure D-1 was used to make a template of 10 times the final device size by DYCRIL process. The film used was CRONAFLEX of thickness 0.007 inches. This was not the type (CRONAR ORTHO D of density

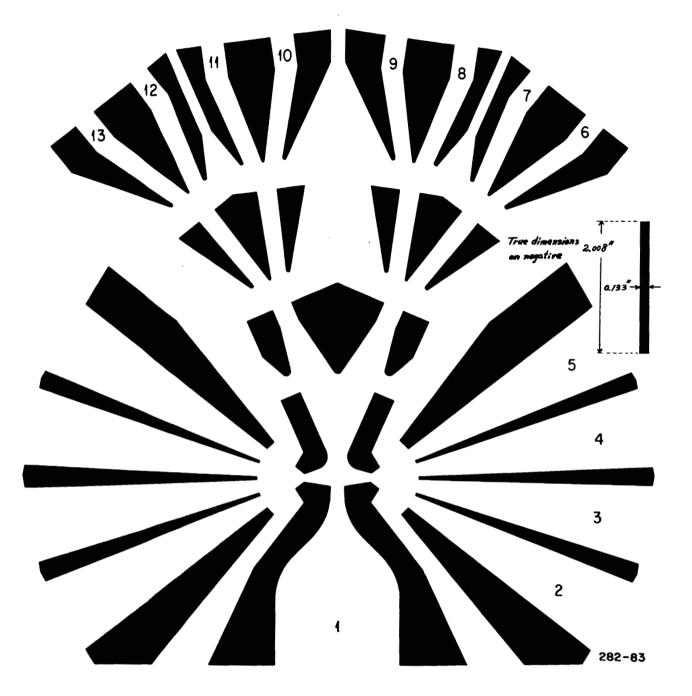


Figure D-1. Template for DOI No. 2 Design

above 4) suggested by Dr. G. Michel of the DuPont Printing Plate Laboratory in Philadelphia, who provided the necessary assistance and laboratory facility to make the test template.

The equipment and procedures are well-developed and established by DuPont and are described in their published literature. It is important, however, to give a sketch of the relative positions of the light source,

the negative, the DYCRIL plate, and the test sample in order to analyze the test result.

### B. Test Results

The test sample consists of 4 blocks which were prepared in the following manner. An area of approximately 1-1/4 inches by 3/4 inch at the location as shown in Figure D-2 was sawed off from the template, and then it was subdivided into 4 blocks. The end faces of each block are lapped carefully to obtain a flat, smooth surface for the photographic analysis.

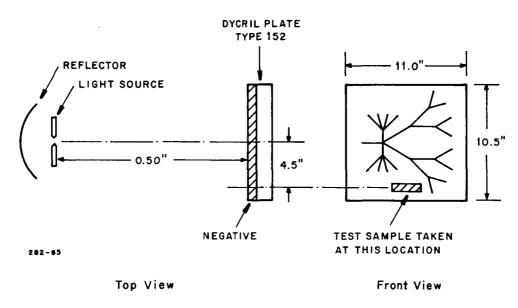


Figure D-2. Schematic Showing Exposure of the DYCRIL Plots

Figure D-3 shows the top view of the blocks at 7.5 times the original size and indicates the end view of each block. Photographs of the end views of 65.2 times the original dimension of the test blocks are shown in Figures D-5, D-6, D-7, and D-8. In essence, the test consists of measuring the dimensions of the "ridge" in these four figures and making comparison with the dimension on the negative and the specification given by the DuPont Company.

In the following, the result and discussion of the test are reported from the viewpoint of a fluid amplifier designer.

(1) Considering the optics involved in DYCRIL process, it is reasonable to assume that the top width of the ridge measured in Figures D-4, D-5, D-6, and D-7 should be very close to the corresponding dimension on the negative. The width of the ridge on the negative is 0.133 inches  $\pm 0.0005$  inches, and both sides are parallel when observed under an optical comparator.

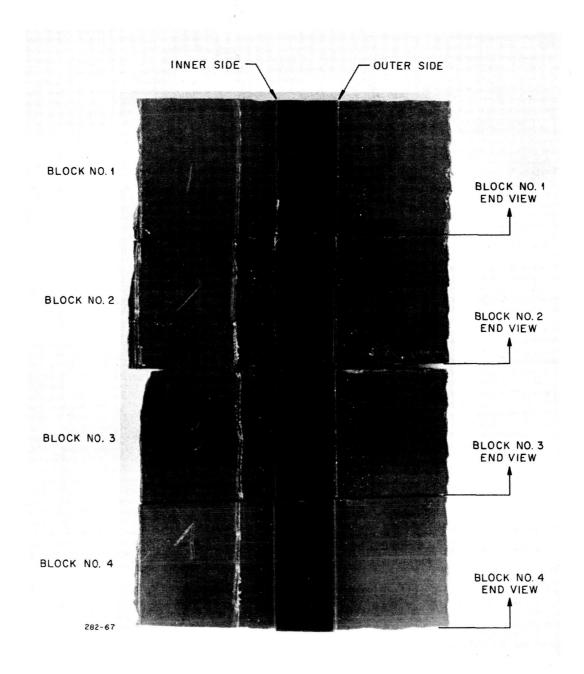


Figure D-3. Top View of the Test Blocks

The top width measured from the photographs are:

Block No. 1 0.1334 inch  $\pm 0.003$  inch (tolerance due to measurement)

Block No. 2 0.1307 inch ±0.003 inch Block No. 3 0.1350 inch ±0.003 inch Block No. 4 0.1350 inch ±0.003 inch

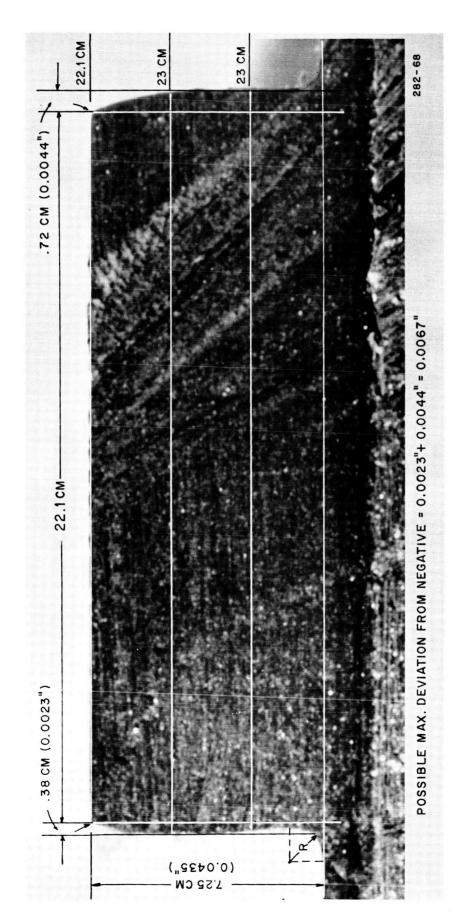


Figure D-4. Block No. 1, End View

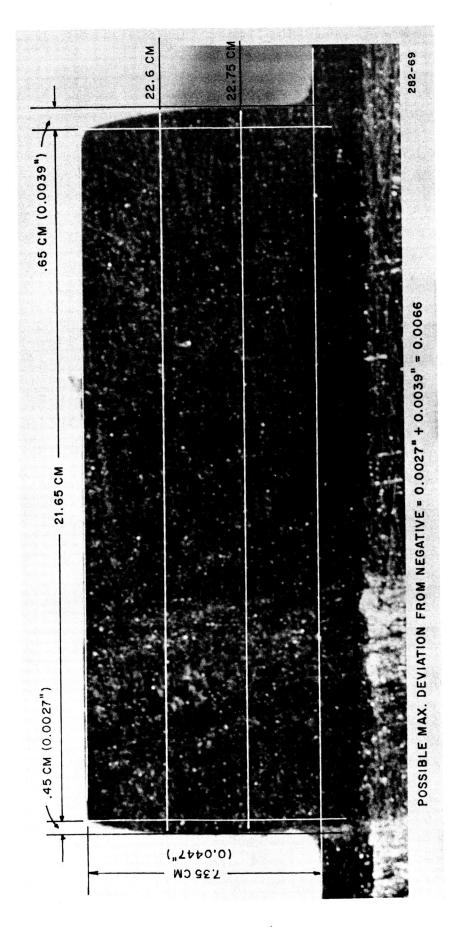


Figure D-5. Block No. 2, End View

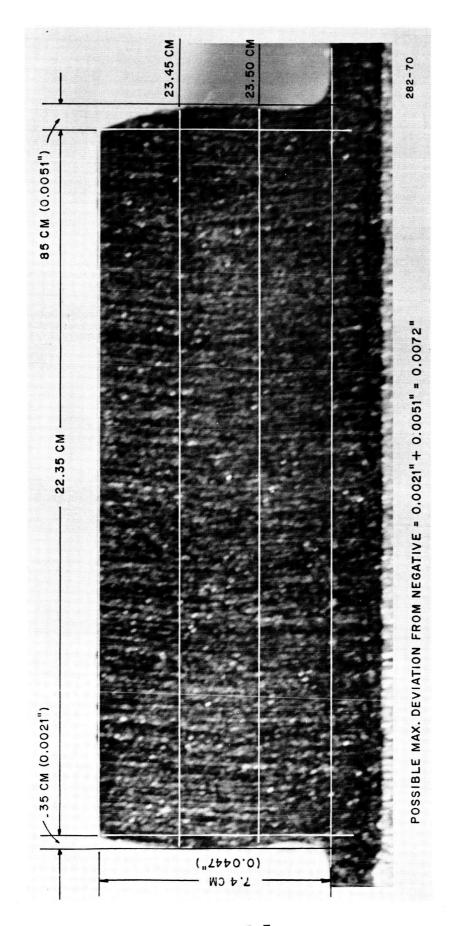


Figure D-6. Block No. 3, End View

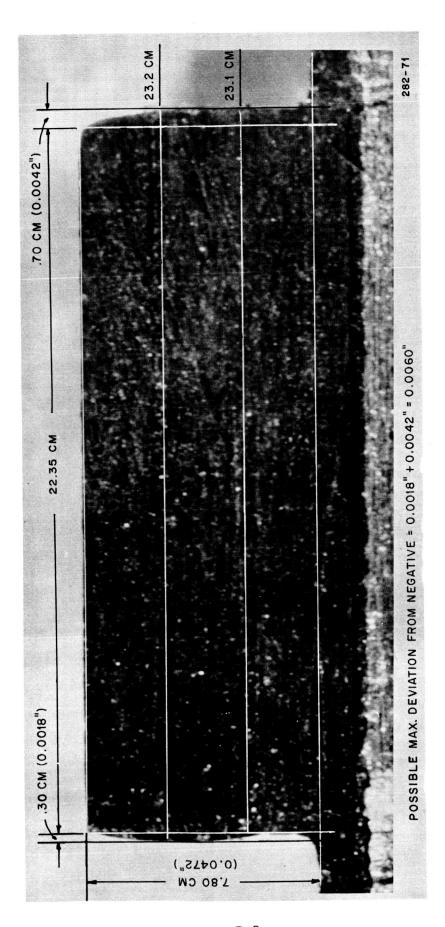


Figure D-7. Block No. 4, End View

Therefore, it can be reduced from these data that for a given straight line with a fixed width on the negative, DYCRIL process is capable of reproducing this line on the surface of the DYCRIL plate with tolerance of  $\pm 0.0021$  inches.

(2) According to DuPont Company's specification for the Type 152 plate, the relief is 0.040 inches. The measured depths from the photographs are:

Block No. 1 0.0435 inch  $\pm 0.0003$  inch Block No. 2 0.0447 inch  $\pm 0.0003$  inch Block No. 3 0.0447 inch  $\pm 0.0003$  inch Block No. 4 0.0472 inch  $\pm 0.0003$  inch

The data indicates that the process has the tendency of overetching and that the uniformity is subject to several thousands of an inch variation at different sections.

(3) The shape of the sides of the ridge indicates a consistent "S" shape, more pronounced on the inner side than the outer side with respect to the light source. Since the tracing styles of the pantograph follow the outer edge of the "S" shape, the possible deviation in the channel width of the fluid device made by using this template can be estimated in the following manner: (refer to D-8)

Possible deviation from negative = a + b

The effect is to give a narrower channel width than desired.

The measurements on the photographs are given below:

	<u>a(±0.003")</u>	<u>b(±0.0003")</u>	Possible deviation from Negative
Block No. 1	0.0023"	0.0044"	0.0067"
Block No. 2	0.0027"	0.0039"	0.0066"
Block No. 3	0.0021"	0.0051"	0.0072"
Block No. 4	0.0018"	0.0042"	0.0060"

In short, the present process always gives a narrower channel size than design size by the amount as shown above.

The "S" shape of the sides of the ridge is quite different from what is expected, and the explanation for this at present is not clear. A rough estimate of the radius R gives an amount of about 0.004 inch.

(4) The time required for the processes which employ photographic work are:

DYCRIL Process 0.5 - 1.0 hour
Photosensitive
Glass Process
Photosensitive
Ceramic Process 12 hours

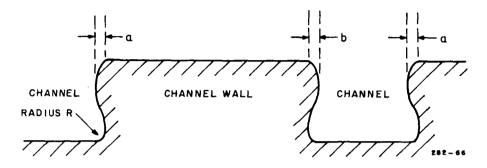


Figure D-8. Cross Section of the Test

# D-3. CONCLUSIONS

From the standpoint of a fluid amplifier designer, it is obvious that the tolerance of the DYCRIL process as reported here must be improved if it is to be used to fabricate the device directly. However, if the process is adopted to make the template for pantograph with a scale of 7 or more (ratio of template to actual device size), DYCRIL process will give an excellent result.

### APPENDIX E

### REFERENCES

<sup>&</sup>lt;sup>1</sup>Raymond N. Auger, "The Turbulence Amplifier in Control Systems," <u>Proceedings</u> of the Fluid Amplification Symposium, May 1964, Volume II.

T. A. Shook, "Pure Fluid Binary Counter Design," Final report for the Harry Diamond Laboratories, Washington 25, D.C., Contract No. DA-49-186-AMC-34(X), March 1964.

<sup>&</sup>lt;sup>3</sup>Herman Schlichting, <u>Boundary Layer Theory</u>, New York: McGraw-Hill, 1960.

<sup>&</sup>lt;sup>4</sup>"Development of a Pure Fluid Flip-Flop," UNIVAC Final report under contract No. 13-7440 for Sandia Corporation, Albuquerque, New Mexico, August 12, 1964.